VOLUME 1

FINAL REPORT OF THE SPACE SHUTTLE PAYLOAD PLANNING WORKING GROUPS

ASTRONOMY

MAY 1973

NATIONAL AERONAUTICS & SPACE ADMINISTRATION

GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND 20771

(NASA-TM-X-69409) THE SPACE SHUTTLE PAYLOAD PLANNING WORKING GROUPS. VOLUME 1: ASTRONOMY Final Report (NASA) 80 p HC $6.00 CSCL 22B

N74-15518

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GLOSSARY

Abbreviation	Description
AMB	Astronomy Mission Board
EVA	Extra Vehicular Activity
HEAO	High Energy Astronomy Observatory
IME	International Magnetospheric Explorer
IUE	International Ultraviolet Explorer
KWOT	Kilometer Wave Orbiting Telescope
LAE	Lyman Alpha Explorer
LH_2	Liquid Hydrogen
LHe	Liquid Helium
LST	Large Space Telescope
MJS	Mariner-Jupiter-Saturn (Mission)
NEP	Noise Equivalent Power
OTA	Optical Telescope Assembly for LST
SI	Scientific Instrument System for LST
SOREL (Project)	A Drag-Free Solar Orbiting Satellite
SRT	Supporting Research and Technology
SSM	Support System Module for LST
VLBI	Very Long Base Line Interferometry
XUV	Extreme Ultraviolet

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FOREWORD*

In January 1972 the United States decided to develop a new space transportation system, based on a reusable space shuttle, to replace the present expendable system.

By January 1973 planning had progressed to the point that through the European Space Research Organization (ESRO) several European nations decided to develop a Space Laboratory consisting of a manned laboratory and a pallet for remotely operated experiments to be used with the shuttle transportation system when it becomes operational in 1980.

In order to better understand the requirements which the space transportation must meet in the 80's and beyond; to provide guidance for the design and development of the shuttle and the spacelab; and most importantly, to plan a space science program for the 80's to exploit the potential of the shuttle and the spacelab, the United States and Europe have actively begun to plan their space programs for the period 1978–1985, the period of transition from the expendable system to the reusable system. This includes planning for all possible modes of shuttle utilization including launching automated spacecraft, servicing spacecraft, and serving as a base for observations. The latter is referred to as the sortie mode. The first step in sortie mode planning was the Space Shuttle Sortie Workshop for NASA scientists and technologists held at the Goddard Space Flight Center during the week of July 31 to August 4, 1972. For the purposes of that workshop, shuttle sortie missions were defined as including those shuttle missions which employ observations or operations (1) from the shuttle itself, (2) with subsatellites of the shuttle, or (3) with shuttle deployed automated spacecraft having unattended lifetimes of less than about half a year.

In general the workshop was directed towards the education of selected scientists and other personnel within NASA on the basic capabilities of the shuttle sortie mode and the further definition of how the sortie mode of operation could benefit particular disciplines. The specific workshop objectives included:

- Informing potential NASA users of the present sortie mode characteristics and capabilities
- Informing shuttle developers of user desires and requirements
- An initial assessment of the potential role of the sortie mode in each of the several NASA discipline programs
- The identification of specific sortie missions with their characteristics and requirements

*Reprinted from the volume entitled "Executive Summaries".

- The identification of the policies and procedures which must be changed or instituted to fully exploit the potential of the sortie mode
- Determining the next series of steps required to plan and implement sortie mode missions.

To accomplish these objectives 15 discipline working groups were established. The individual groups covered essentially all the space sciences, applications, technologies, and life sciences. In order to encourage dialogue between the users and the developers attendance was limited to about 200 individuals. The proceedings were, however, promptly published and widely distributed. From these proceedings it is apparent that the workshop met its specific objectives. It also generated a spirit of cooperation and enthusiasm among the participants.

The next step was to broaden the membership of the working groups to include non-NASA users and to consider all modes of use of the shuttle. To implement both objectives the working group memberships were expanded in the fall of 1972. At this time some of the working groups were combined where there was appreciable overlap. This resulted in the establishment of the 10 discipline working groups given in Attachment A. In addition European scientists and official representatives of ESRO were added to the working groups. The specific objectives of these working groups were to:

- Review the findings of the GSFC workshop with the working groups
- Identify as far as possible the missions (by mode) that will be required to meet the discipline objectives for the period 1978 to 1985
- Identify any new requirements or any modifications to the requirements in the GSFC report for the shuttle and sortie systems
- Identify the systems and subsystems that must be developed to meet the discipline objectives and indicate their priority and/or the sequence in which they should be developed
- Identify any new supporting research and technology activity which needs to be initiated
- Identify any changes in existing procedures or any new policies or procedures which are required in order to exploit the full potential of the shuttle for science, exploration and applications, and provide the easiest and widest possible involvement of competent scientists in space science
- Prepare cost estimates, development schedules and priority ranking for initial two or three missions

In order to keep this planning activity in phase with the shuttle system planning the initial reports from these groups were scheduled to be made available by the spring of 1973. It was also felt necessary that the individual working group activities be coordinated both between the groups and with the shuttle system planning. As a result, the steering group given in Attachment B was established.

Early in 1973, NASA and the National Academy of Sciences jointly decided that it would be appropriate for a special summer study to review the plans for shuttle utilization in the science disciplines. This summer study has now been scheduled for July 1973. It is anticipated that the results of the working group activities to date will form a significant input into this study.

In the following sections of the summary document are the executive summaries of each of the working group reports. While these give a general picture of the shuttle utilization plan, the specific plan in each discipline area can best be obtained from the full report of that working group. Each working group report has been printed as a separate volume in this publication so that individuals can select those in which they are particularly interested.

From these working group reports it is apparent that an appreciable effort has been made to exploit the full capability of the shuttle. It is, however, also apparent that much work remains to be done. To accomplish this important work, the discipline working groups will continue.

Finally it is evident from these reports that many individuals and groups have devoted appreciable effort to this important planning activity. I would like to express my appreciation for this effort and stress the importance of such activities if we are to realize the full potential of space systems in the 1980s.

John E. Naugle

John E. Naugle, Chairman
NASA Shuttle Payload Planning
Steering Group

LIST OF WORKING GROUPS

	GROUP NAME	CHAIRMAN	CO-CHAIRMAN
1.	ASTRONOMY	Dr. N. Roman (HQ)	Dr. D. S. Leckrone (GSFC)
2.	ATMOSPHERIC & SPACE PHYSICS	Dr. E. Schmerling (HQ)	Mr. W. Roberts (MSFC)
3.	HIGH ENERGY ASTROPHYSICS	Dr. A. Opp (HQ)	Dr. F. McDonald (GSFC)
4.	LIFE SCIENCES	Dr. R. Hessberg (HQ)	Dr. D. Winter (ARC)
5.	SOLAR PHYSICS	Dr. G. Oertel (HQ)	Mr. K. Frost (GSFC)
6.	COMMUNICATIONS & NAVIGATION	Mr. E. Ehrlich (HQ)	Mr. C. Quantock (MSFC)
7.	EARTH OBSERVATIONS	Dr. M. Tepper (HQ)	Dr. W. O. Davis (DoC/NOAA)
8.	EARTH AND OCEAN PHYSICS	Mr. B. Milwitzky (HQ)	Dr. F. Vonbun (GSFC)
9.	MATERIALS PROCESSING AND SPACE MANUFACTURING	Dr. J. Bredt (HQ)	Dr. B. Montgomery (MSFC)
10.	SPACE TECHNOLOGY	Mr. D. Novik (HQ)	Mr. R. Hook (LaRC)

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COORD./Mitchell

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- SOLAR PHYSICS/Oertel
- HIGH-ENERGY ASTROPHYSICS/Opp
- ATMOSPHERIC & SPACE PHYSICS/Schmerling

APPLICATIONS WORKING GROUPS

COORD./Jaffe

- COMM. & NAV./Ehrlich
- EARTH & OCEAN PHYSICS/ Milwitzky
- EARTH OBSERVATIONS/ Tepper
- MATERIAL SCIENCE & SPACE PROCESSING/Bredt

LIFE SCIENCE WORKING GROUP

COORD./White

- LIFE SCIENCE/Hessberg

SPACE TECHNOLOGY WORKING GROUP

COORD./Hayes

- SPACE TECHNOLOGY/ Novik

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ASTRONOMY WORKING GROUP

EXECUTIVE SUMMARY

The principal advantages of space astronomy over ground-based observations reside in the greatly increased spectral coverage and angular resolution attainable from above the earth's atmosphere. For the first time celestial objects can be studied over virtually the entire electromagnetic spectrum from radio to gamma-ray frequencies. Even at the present early stage, this ability has produced a number of major surprises - for example, the overwhelming infrared emission from a variety of objects including planetary nebulae and galactic nuclei. Higher angular resolution will not only permit more detailed study of the structure of individual objects but, because of night sky suppression, will also allow observation of substantially fainter and hence more distant sources. By exploiting these advantages during the coming decades we will be able to solve, or at least to greatly increase, our understanding of such major scientific problems as the evolution of the early universe, the nature of quasars, galactic nuclei and radio sources, the formation of galaxies and of the stars within them, the origin of the chemical elements, and the origin of the solar system and of life itself. Solutions to these problems will impact all branches of human endeavor that have been seriously hampered in the past by the limited view of the universe available from the ground.

The immense potential of space astronomy has been amply demonstrated during the last decade with comparatively small, exploratory instruments, limited to the observation of relatively bright sources. The time is now appropriate to establish in space the full range of observing facilities required to solve long-standing astronomical problems. The advent of the Space Shuttle renders this not only technically feasible but even moderately inexpensive as compared to earlier ventures in space science.

The cornerstone of our recommendations for the 1980's is the Large Space Telescope (LST), a three meter aperture, diffraction-limited telescope optimized for the ultraviolet and visible regions of the spectrum but usable also in the infrared. It will be operated as an automated satellite and will be periodically serviced by the Shuttle. The LST will extend significantly the distance to which we are able to probe the universe and offers, for example, a prospective solution to the cosmological problem, which has not proved possible from the ground. A balanced program requires that this major instrument be supplemented by other more specialized instruments, as indeed are also required in ground-based observatories.

Because the LST is not planned primarily for the infrared, early emphasis in the Shuttle Sortie program is placed on this spectral region. Two infrared telescopes are proposed.

- A 1.5-meter aperture telescope, cryogenically cooled to about 20°K specifically for the 10-50 μm wavelength region.
- A very large uncooled telescope for the far-infrared and microwave region, and for planetary studies and narrow-band spectroscopy over the whole infrared range.

Although both telescopes could operate as automated free-flyers based on the same spacecraft Support System Module (SSM) developed for the LST, both would gain by operation on the Shuttle. For the uncooled telescope the Shuttle allows the accommodation of larger optics than would be possible with the Titan-compatible SSM, as well as the possibility of interchanging instruments at the focal plane during flight. The cryogenic system for the cooled telescope would be much simpler and less expensive on the Shuttle. These telescopes will be powerful tools in the exploration of such diverse phenomena as the immense infrared energy output of galactic nuclei, the conditions in the interstellar medium leading to star formation, and the physical properties and composition of planetary atmospheres and surfaces.

In the ultraviolet, there is a definite need for a wide angle telescope to provide a UV survey in one broad wavelength band if the LST is to be used for many years to maximum effect. Subsequent use for studies at different wavelengths or for an ultraviolet spectral survey would be valuable but less urgent. A one meter diffraction-limited telescope for the ultraviolet and visible will provide high angular resolution imaging over relatively wide fields of view (0.5°). Such a capability is required, for example, for photometric studies of stellar evolution in globular and open clusters and to supply observations of nearby galaxies as the basis for LST studies of faint ($>21^m$) extragalactic sources. Unless or until the LST makes possible the frequent monitoring of solar system bodies, the 1-meter telescope can provide the needed synoptic coverage. The major advantage of the Shuttle for both these instruments is that it will allow use of photographic and electronographic detectors with their very large information storage capability. The 1-meter telescope will also provide an important test bed for auxiliary instrumentation for LST, allow specialized observations of a "one-of-a-kind" nature and relieve LST of observations of relatively bright sources.

In addition to these five instruments, which the panel considered in detail, several other instruments which were considered briefly are typical of those which the Shuttle program should include. Examples are a very wide angle ultraviolet camera for the study of large scale, low surface brightness nebulae and star clouds, a grazing incidence telescope for the extreme ultraviolet between the normal X-ray region and the Lyman limit of hydrogen, Explorer-class free flyers (to measure the cosmic microwave background for example), and rocket-class instruments which can fly frequently on a variety of missions.

Except for the LST, each of the major astronomy instruments requires approximately half of the space, weight, and other support of a Sortie flight. While each could be operated remotely from the ground, our present impression is that in most cases it would be preferable to have the support of a four man Shuttle crew, in addition to the pilot and co-pilot, and a small laboratory to provide workspace, data storage, communications and access to the focal plane of at least one telescope. Although the individual instruments could share a Sortie mission with another discipline, compatibility requirements are severe. Astronomy requires stabilization of the Shuttle to near one arc minute (by means of control moment gyros), control of the pallet pointing direction throughout operation as dictated by the astronomical program, and a contamination-free environment. We therefore believe that we would be our own best companion. Most scientific direction must be from the ground, making it necessary to have excellent communication, including picture transmission, on both up and down links. A data relay satellite would be very helpful, although astronomy can use the intermittent communication provided by a ground network of tracking stations if adequate capacity compensates for limited time and if real-time communications are possible from the receiving station to a central control station at the same rate.

REPORT OF THE ASTRONOMY WORKING GROUP

INTRODUCTION

The Astronomy Working Group for the Space Shuttle represents a consolidation and reconstitution of three Working Groups of the 1972 Space Shuttle Sortie Workshop at the Goddard Space Flight Center, namely the panels in UV-Optical, Infrared and Planetary Astronomy. The membership is divided about equally between astronomers from NASA and from the community at large. The domain of this Working Group covers wavelengths of the electromagnetic spectrum $\gtrsim$ 20 nm and all astronomical objects except the sun and the earth, although earth observations bearing on other planets are included. Two fields, relativity and long-wave radio astronomy, were relegated to subpanels, whose conclusions are summarized in the appendices of this report.

During three meetings of the Working Group and in individual assignments, from November 1972 to April 1973, we have attempted to identify the salient contributions of the Shuttle to astronomical research in the 1980's and to assess the possible impact of space astronomy on Shuttle design and operations. Our first task was to decide which astronomical programs are likely to be timely for the 1980's and which might profit from space observations. We then defined and discussed the instrumentation required for such research. Emphasis was placed on the necessity for a balanced program of space astronomy and a balanced complement of instrumentation, likely to be applicable to a wide range of research areas, regardless of our present ability to identify those areas.

It was assumed that the Space Shuttle will be the primary, and perhaps the only, major launch vehicle available for astronomy in the 1980's. We further assumed that the Shuttle will be used in several different ways:

- To carry automated satellites to near-earth orbit, from which they may be launched to higher altitudes with additional booster stages.
- To launch major automated satellites into near-earth orbit and to provide revisit and maintenance opportunities.
- To carry observatory instruments into orbit, to provide basic facilities for their use in orbit and to return them to earth after periods of 7 to 30 days (Sortie missions).

All three modes will be actively exploited by space astronomy in the Shuttle era.

SPACE-RELATED ASTRONOMICAL PROGRAMS FOR THE 1980's

Modern astronomy is characterized by striking and unexpected discoveries, and many of the most interesting areas of astronomical research in the 1960's and 70's were entirely or largely unforeseen in the 1950's. These discoveries include quasars, pulsars, black holes, interstellar molecules and masers, energetic processes in the nuclei of galaxies, the $3^{\circ}K$ cosmic background radiation, and a cratered and volcanic Martian surface. Similarly, many of the problems of compelling interest to astronomers in the 1980's and 1990's are probably beyond our present powers of prophecy. On the other hand the frontiers of astronomical research in many areas can be rather clearly defined. The great promise of space astronomy in the Shuttle era is that we will be able to fully exploit the environment above the earth's atmosphere, on a more or less routine basis, with a broad range of instrumentation, to push back those frontiers. The freedom from atmospheric extinction, emission and scintillation and from variable seeing not only will allow one to sample nearly the full wavelength range of electromagnetic radiation emitted by astronomical sources but will also allow the imaging of sources to limiting magnitudes and with angular resolution unparalleled in ground-based astronomy.

As a prelude to our discussion of instrumentation we compiled a preliminary list of more than 40 investigations which we expect to be of interest to astronomers in the 1980's and which would benefit from space observations. On the basis of this list we defined a complement of instruments which would usefully exploit the potential of space astronomy. We believe that this ensemble of instruments, described in the pages which follow, is reasonably comprehensive and well-balanced and that it will weather most changes in the emphasis of astronomical research over the next two decades. Some elaboration of scientific programs to which each instrument is applicable is given; however, no attempt at completeness in the definition of such programs has been made.

THE TOOLS OF SPACE ASTRONOMY IN THE SHUTTLE ERA

OVERVIEW AND PRIORITIES

Space astronomy in the 1980's will require a wide diversity of instrumentation ranging in size and complexity from the Large Space Telescope (LST) to small rocket-class instruments. These fall into three categories:

- Major facility telescopes applicable to a broad range of astronomical problems, useful to a large cross-section of the astronomical community and involving costs on the order of tens of millions of dollars. Some of these will be used in free-flying satellites with Shuttle maintenance. Others will fly in the Shuttle Sortie mode on dedicated or semi-dedicated astronomy missions.

- Free-flying, automated Explorer satellites dedicated to the solution of specific astronomical problems. These will require check-out and launch from the Shuttle but may otherwise be independent of Shuttle or Sortie operations.

- Relatively small rocket-class or Explorer-class experiments utilized primarily in the Shuttle Sortie mode. Such devices will allow individual researchers or groups the opportunity of conducting a wide variety of essentially closed-ended observing programs, with the duration of observations, spacecraft support facilities and operational flexibility far exceeding that now available in rocket astronomy. They will fly as "piggy-back" instruments on missions not necessarily dedicated to astronomy, although some inertial pointing will usually be required.

Individual Shuttle payloads may include combinations of these three classes of instruments. For example, the Shuttle launch of an automated Explorer could be followed for the balance of the mission by observations with a major facility telescope.

The Astronomy Working Group has placed strong emphasis on the definition of major facility telescopes for space astronomy, not only because of their wide applicability and potential interest to the astronomical community, but also because they will have the strongest impact on Shuttle planning and design and on program costs. It is not our intention to minimize the importance of the smaller "piggy-back" experiments. Several examples of Sortie payloads and automated Explorers have been defined. It is difficult to attach priorities fairly to such a wide range of scientific instruments, i.e., to compare on the same basis an LST with a small rocket experiment. Prioritization within each of the three instrument categories is perhaps a more sensible approach.

We strongly endorse the Large Space Telescope as the primary facility for space astronomy in the 1980's. Highest priority must be attached to its continued development and implementation. Although the LST has been considered principally as a UV-Optical instrument, we wish to emphasize its potential usefulness in the near infrared as well.

In addition to the LST we recommend the development of the following major instruments:

- A 1.5 meter infrared telescope, cryogenically cooled to about 20° K (e.g., liquid hydrogen).

- A very large aperture (4 meters or larger) infrared telescope, radiatively cooled to below 200° K.

- As many as three all-reflecting Schmidt cameras for a complete, deep-sky survey in the ultraviolet.

- A 1-meter diffraction limited UV-optical telescope.

These five telescopes constitute a balanced ensemble of instruments for achieving many of the objectives of ultraviolet, optical and infrared astronomy in the 1980's. To some degree the functions of these instruments overlap. However, each possesses unique capabilities which make it the best telescope of the five for particular programs of research. Each complements other instruments in the group. In the infrared the wavelength range 0.7–10μm should be covered primarily by the LST. The 1.5 m cooled telescope will be optimized for the middle infrared (10–50μm) and for observations requiring large bandwidths and wide fields of view. The very large aperture uncooled telescope will be required at far-infrared wavelengths (50μm–1.7 mm or longer) to provide high angular resolution over narrow fields of view and large light gathering power for narrow-band spectroscopy. For UV-optical space astronomy the LST will provide unique capabilities for observations to very faint limiting magnitudes, for observations requiring very high angular resolution over small fields of view, and for high resolution spectroscopy. The 1-meter diffraction limited telescope will be capable of precise imaging at high angular resolution over relatively wide fields of view ($\approx 0.5°$), and precise broad or intermediate-band photometry of objects of moderate brightness. In addition, it will be an excellent test bed for LST auxiliary instrumentation. The all-reflecting Schmidt cameras will be capable of quickly and efficiently obtaining qualitative photometric and spectral data on all stars to a faint limiting magnitude over the entire sky.

MAJOR FACILITY TELESCOPES

The Large Space Telescope (LST)

The LST (Figure 1) will consist of three basic elements, an optical telescope assembly (OTA), a scientific instrument system (SI) and a support system module (SSM). The nucleus of the OTA will be a 3-meter aperture, f/12 Ritchey-Chretien telescope configured to deliver images of excellent quality over a relatively narrow field of view. Angular resolution of about 0.05 arc sec at 633 nm over a 5 arc min diameter field is expected, with lower resolution performance over a total field of 24 arc min. The LST guidance system will provide a stability of 0.005 arc sec rms. This performance is to be compared with the 0.5 arc sec resolution available on rare occasions at superb terrestrial sites. The reduction of image sizes by factors ranging from 10 to 50, with a consequent rejection of sky background, coupled with a reduction in the brightness of the sky background and an absence of significant atmospheric extinction in space, imply that the LST will be able to observe objects some 20 to 100 times (3 to 5 magnitudes) fainter and brighter objects with greater speed than is now possible on the ground.

The optical system will provide high transmission of light from about 0.11μm in the ultraviolet to the longest infrared wavelength for which it can be designed without adversely affecting the ultraviolet and visual performance of the telescope (believed to be at least 20μm). Ground-based instruments are limited by atmospheric obscuration to wavelengths ranging from about 0.3μm to about 1μm, with a few spectral "windows" available farther in the infrared.

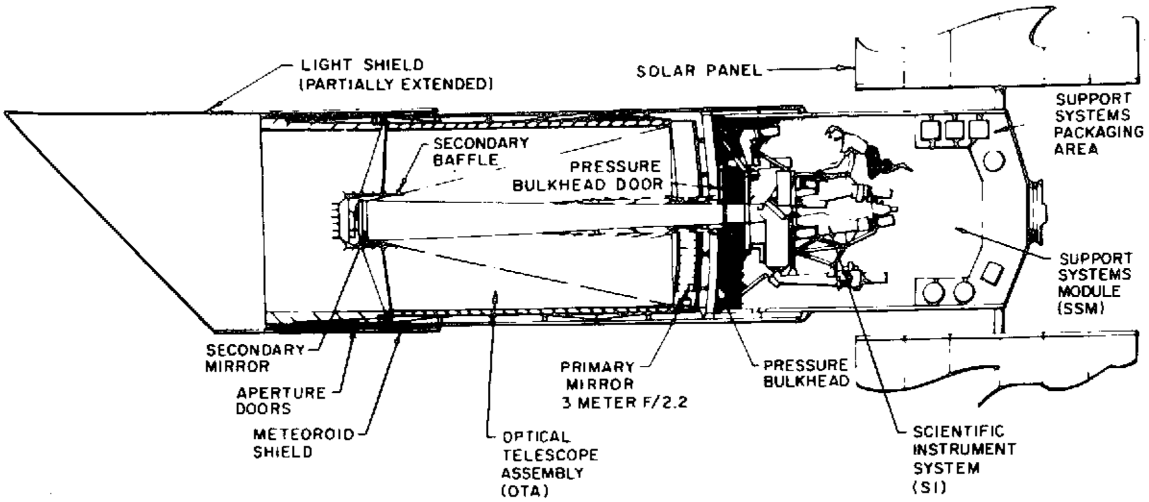


Figure 1. The Large Space Telescope*

Studies to date suggest that the LST will contain three basic scientific instruments:

- A high angular resolution camera, designed to match the resolution capabilities of the telescope to the available detectors. A 36 arc sec field of view appears to be the largest field which will fit current remote-readout detectors at the diffraction-limited resolution of the telescope. The usefulness of wider fields (say 50-100 arc sec) for certain astronomical programs requiring very high resolution imaging should provide impetus to the development of detectors with higher linear resolution. Selectable filters will define the camera's bandwidth within the operating range of 110-1100 nm.

- A high spectral resolution spectrograph with resolving power $\lambda/\Delta\lambda \geq 3 \times 10^4$, operating over the 110-350 nm range.

- A low spectral resolution spectrograph optimized for observation of faint objects. Resolving power will be $\geq 10^3$ with an operating range 0.11 μm to 5 μm.

Typical additional instruments might include a very high spectral resolution spectrograph ($\lambda/\Delta\lambda = 3 \times 10^5$), a photometer with the high time resolution (1 - 10 μ sec) capability, a wide field f/12 camera for use in the ultraviolet and over the 3-5 μm range in the infrared, and infrared photometers and spectrometers.

The SSM will provide basic spacecraft functions for the LST observatory, including power, guidance, thermal control, data processing and telemetry,

*Although the LST will be an automated satellite, it is illustrated here in a possible manned-maintenance mode.

command memory storage, etc. The basic LST-SSM might be used as a standard spacecraft, adaptable to other major space telescopes, including some of the major facility telescopes discussed below. The replication costs for SSM's should be substantially less than the cost of the initial unit developed for the LST.

The LST will be a versatile, long-lived international observatory. Repair and maintenance, through use of the Space Shuttle, will enhance its cost-effectiveness, by ensuring a long lifetime. The ability to periodically alter the auxiliary instrument complement of the LST will ensure that it reflects the research needs of the times and the progressive improvement of instrumental capabilities.

A 3 to 5 magnitude, or greater, increase in the faintest observable limiting magnitudes; the capability for high angular resolution imaging; and the extension of astronomical spectroscopy to wavelengths and limiting magnitudes beyond the capabilities of ground-based instruments, will allow attack on a wide variety of astronomical problems with the LST. Extension of the redshift-diameter and redshift-magnitude diagrams to fainter limiting magnitudes of distant galaxies may allow astronomers to choose among various cosmological models on the basis of the observed deceleration parameter, q. At the other extreme, synoptic imaging and spectroscopy of the planets will test structural and dynamical models of planetary atmospheres. At intermediate distances, the fainter members of star clusters can be studied photometrically and spectroscopically, stellar populations in selected regions of nearby galaxies can be analyzed and the nuclei of galaxies can be better resolved. Astrometric programs exploiting the LST's small image size, and resolution and spectroscopy of binary companions with small angular separation, will yield improved knowledge of the distances and masses of nearby stars and may allow the detection of other planetary systems. A detailed discussion of the scientific potential of the LST in a broad range of research areas may be found in "Scientific Uses of the Large Space Telescope" (1969, Space Science Board, National Academy of Sciences, Washington, D.C.) The usefulness of the LST at infrared wavelengths, however, was barely discussed in this study. Although the LST will not be optimized for infrared observations, it can provide unique information if instrumented suitably. One important program would involve high resolution spectroscopy of molecular bands at wavelengths $< 5\,\mu m$, allowing the detection of trace molecular column densities in stars or protostars, in the interstellar medium and on the planets.

A 1.5 Meter Cryogenically-Cooled Infrared Telescope

A large group of interesting and important astronomical objectives can be achieved by a moderately large, cooled telescope in space. An instrument of this sort would be optimized for observations in the 10-50 μm region with a capability for low-resolution spectroscopy or broad-band photometry of faint or extended sources over a wider range, roughly from 5 to 200 μm. Observations at these wavelengths are impossible from the earth's surface because of absorption by atmospheric water vapor and CO_2 throughout the 5-500 μm range, except for spectral "windows" near 10μm and 20μm. Airborne telescopes offer limited observing above most of the absorbing water vapor and balloon-borne telescopes at 100,000 feet suffer very little from absorption. However, even at 100,000 feet the detectors in such telescopes receive far more radiation from atmospheric emission and from their own optics than from any astronomical object outside the solar system. Various schemes for background radiation subtraction are used, but a limit in sensitivity is set by statistical fluctuations in the background radiation (background noise). These can be reduced only by reducing the background radiation itself. The latter reduction may be accomplished either by working in a narrow spectral band or in a narrow field of view or both. In applications where such limitations cannot be tolerated (e.g., Fourier spectroscopy, broad-band photometry of extended sources, observations of faint sources) the solution is to cool the optics and get well above the earth's atmosphere.

The greatest sensitivity can be achieved by reducing background noise below the detector noise level. Detectors with noise-equivalent power (NEP) of 10^{-16} watts $hz^{-1/2}$ have been built for use in the 10-30μm range. At longer wavelengths NEP's of 10^{-14} watts $hz^{-1/2}$ are reported, but much higher sensitivity may be attainable by the 1980's. Even with a diffraction-limited field of view a telescope operating in the 10-50μm band would have to be cooled to below 40°K, assuming 0.05 emissivity, to take full advantage of a 10^{-16} watts $hz^{-1/2}$ detector. If, instead, the surroundings were at 190°K with 0.05 emissivity, (levels achievable in space with passive, radiative cooling) the background noise would be 100 times higher. To obtain a measurement with a given signal-to-noise ratio would take 10,000 times as long with the 190°K system as with a system cryogenically-cooled to 40°K or below. For the 1.5m cooled telescope a temperature of $\lesssim$20°K is desirable. Possible coolants would include liquid, solid, or supercritical hydrogen or supercritical helium. Precooling of the telescope on the launch pad will probably be required.

We have suggested an aperture of 1.5 meters, based on rough estimates of size and weight available in the Shuttle Sortie configuration and on the technology of cooled optical systems, but any size above 1 meter would be worthwhile. Alternatively, we might construct an intermediate aperture cryogenically-cooled infrared telescope as a free-flying satellite, with periodic Shuttle maintenance. The LST-SSM might be an appropriate spacecraft in this mode and cryogenic technology developed for the Stanford gyro-satellite might be applicable. The free-flying mode would maximize the available on-orbit observing time for the telescope and Shuttle maintenance would allow cryogen replacement, repairs, and instrument updating. However, the cost of a large and reliable cryogenic system, capable of maintaining liquid hydrogen temperatures in the telescope and liquid helium temperatures ($\approx$4°K) in the detectors for 3-6 month periods could be quite high.

The 1.5 m infrared telescope (Figure 2) is envisioned as a Cassegrain with an f/2 primary possessing at least a 0.5° field of view, a modulating secondary mirror, cooled baffles, a movable sun shield and a removable thin plastic window for protection from contaminants during early phases of a mission. The telescope would be mounted on gimbals (possibly on a swing table) on a Sortie pallet and would constitute approximately 1/2 of a Sortie payload. Manned access to the focal plane would not be necessary. A rotatable tertiary mirror in the instrument bay would be commanded to direct the light beam into any of several different instruments. Instruments could be interchanged from mission to mission to accommodate the needs of different investigators. A complement of instruments and detectors might include:

- A broad-band infrared filter photometer using a liquid helium-cooled detector.

- An infrared photoconductor detector array (LHe-cooled doped germanium) for flux measurements with spatial resolution.

- A Fourier spectrometer (LHe-cooled) for medium resolution ($0.1\,cm^{-1}$) infrared spectroscopy.

- An infrared polarimeter (both linear and circular)

- A grating spectrometer with multichannel detectors for intermediate band infrared spectrophotometry.

Rotatable disks between the tertiary and secondary mirrors would contain an assortment of filters and an optional beam chopper.

The cooled infrared telescope would be particularly susceptible to contamination problems in the vicinity of the Space Shuttle. Not only could effluents condense onto the cold optical surfaces, but effluent clouds which absorb, scatter and radiate at infrared wavelengths could seriously degrade the astronomical data. When the emission of condensables from the Shuttle bay and cabin have been minimized, the thin plastic window might be removed. Prior to that the thin window could be cleaned periodically with warm helium and re-cooled with vented cryogen gas. By the use of control moment gyros for Shuttle stabilization, by use of the modulating secondary mirror and possibly by swinging the telescope out of the Shuttle payload bay, such contamination problems may be minimized.

Astronomical research with a 1.5 m cooled infrared telescope would include the following. H I and H II regions could be examined spectroscopically to determine their cooling mechanisms and molecular content. Contributions to the infrared

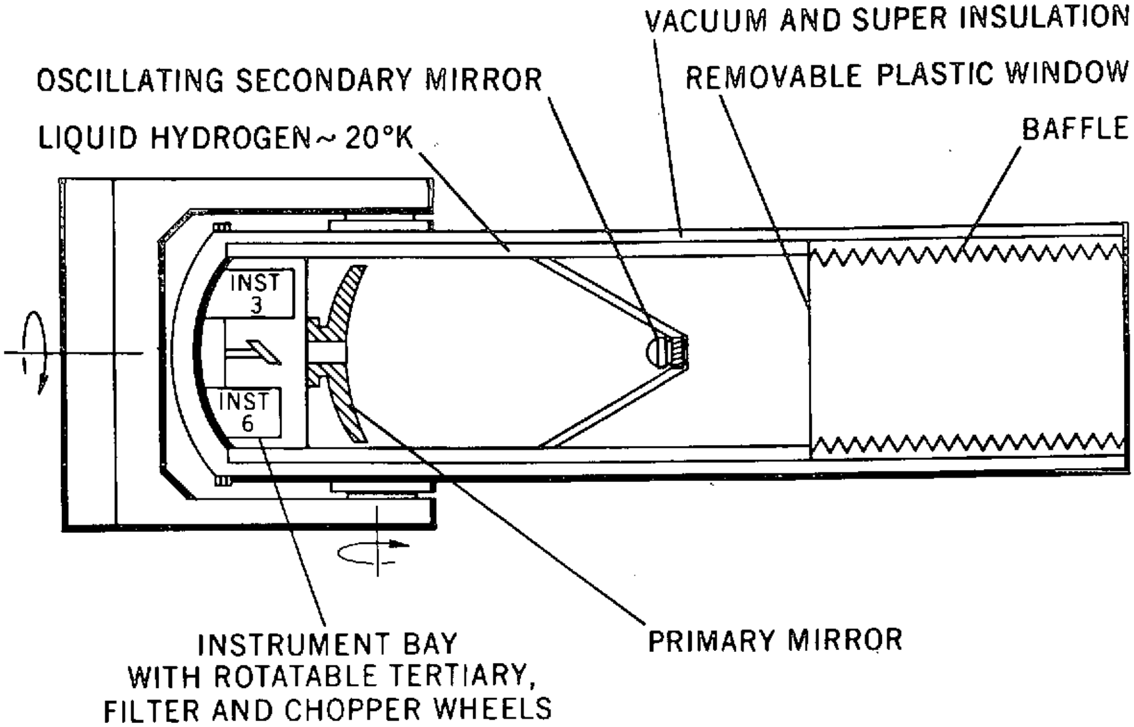


Figure 2. Cooled IR Telescope - Multiple Instrument Bay

radiation are expected from forbidden transitions in atoms and ions, from molecular line radiation and from continuum emission arising mainly from dust. A large number of such sources have been found in a roughly 50 μm band centered at 100 μm. The proposed cooled telescope would be able to do high-resolution spectroscopy of such regions as well as coarse spatial mapping of these and much fainter extended sources. Mapping in the 28 μm line of H_2 would facilitate estimates of the H_2 content of galactic clouds. Mapping in one or more of the HD lines may help to determine the early deuterium content of the galaxy and conditions of the primordial fireball.

Infrared radiation from the nuclei of distant galaxies should be studied spectroscopically and photometrically to gain an understanding of the processes which make some of them so bright at infrared wavelengths. Determinations of their time-variability must be made and the possibility of a systematic dependence of color temperature upon distance (age) should be checked. The need for examining the most distant galaxies possible in the 10-100μm spectral range makes the greatest demands on system sensitivity. Since narrow-band observations are out of the question here and the objects are not point sources, the cooled telescope is by far the most suitable instrument for such work.

Table 1

Limiting Performance of a 1.5 m LH_2 - Cooled Infrared Telescope*

Object	λ (μm)	θ (arcmin)	D (parsecs)	λF_λ (wm^{-2})	D_m (parsecs)	D_θ (parsecs)
0.0 Magnitude A0 Star	10		10	1(-11)	25(2)	
	100		10	1(-14)	20	
α Orionis	10		450	1(-9)	13(5)	
	100			1(-12)	10(3)	
Orion Nebula	100	6	450	1(-8)	1(6)	10(3)
Kleinmann-Low Nebula	10	0.5	450	25(-11)	7(5)	80(3)
	100	1		5(-9)	7(5)	15(2)
	350	1		4(-11)	70(3)	15(2)
Sagittarius B2	100	2	10(3)	4(-9)	13(6)	50(3)
	350	2		6(-11)	17(5)	15(3)
Galactic Center	10	0.4	10(3)	15(-11)	1(6)	150(3)
	100	5		2(-9)	10(6)	200(3)
	100	390		1(-7)	70(6)	15(6)
M82	10	0.5	32(5)	8(-12)	7(8)	60(6)
	100	0.5		6(-11)	7(8)	6(6)
NGC 1068	10	0.02	17(6)	75(-13)	4(9)	
3 C 273	10		12(8)	9(-14)	30(9)	

*Numbers in parentheses are powers of ten.

The proposed telescope will also find applications in deep surveys of portions of the sky, in examining potential non-thermal IR sources, in spectroscopy and polarimetry of circumstellar dust shells, in spectroscopy of the center of our own galaxy and very likely in the examination of many objects and phenomena entirely new to us. Table 1 gives the limiting performance of a 1.5 m LH_2-cooled infrared telescope by listing representative objects which have been observed at infrared wavelengths, λ, and comparing their distances, D, with the distances, D_m, at which similar objects could be observed with the 1.5 m cooled telescope. D_θ is the maximum distance beyond which the extended objects shown, of angular diameter θ, could not be spatially resolved with this telescope. The flux levels actually observed for these objects are denoted by λF_λ. The calculations of D_m assume a signal-to-noise ratio of 1 and a one-second integration time. Detector NEP is taken as 10^{-16} w m^{-2} $hz^{-1/2}$ at 10μm and 2×10^{-15} w m^{-2} $hz^{-1/2}$ at 100μm with assumed transmission efficiency 0.44.

A Very Large ($\geq$4 m) Uncooled Infrared Telescope

At far-infrared and millimeter wavelengths telescopes of small aperture become severely diffraction limited. With minimum observable angular separations given by $1.22\ \lambda/D$ (λ = wavelength, D = aperture), the 1.5 m cooled telescope, described in the preceding Section, could resolve separations no less than 17 arc sec at 100μm, with proportionally lower resolution at longer wavelengths. However, compelling scientific reasons exist for achieving higher angular resolution than this by use of a telescope of the largest feasible aperture. For example, H II regions have been found to contain infrared subcomponents (knots) with sizes and separations of the order of a few tenths of a parsec. At 100μm a 5 m telescope would be able to resolve such subcomponents in H II regions at distances $\lesssim$4000 pc and to distinguish H II regions having separations like those near our galactic nucleus (10-30 arc min) in other galaxies as distant as $1\text{-}3 \times 10^6$ pc. The densities, compositions and excitation of the subcomponents of a given H II region may differ drastically so they must be resolved if infrared data are to be properly understood. High angular resolution will be vital in interpreting observations of far infrared nebular line radiation. Infrared planetary studies such as detailed temperature sounding, spatial constituent mapping and observations of global meteorological phenomena also become possible with such high angular resolution.

The great light-gathering power of a large aperture telescope, not only in the far infrared but over the whole range of infrared wavelengths, should also be emphasized. Narrow-band spectroscopy of interstellar molecular lines, for example, will require a maximum photon-collecting capability. The first observations of such line emission may produce as profound a change in infrared astronomy in the 1980's as did similar observations in radio astronomy in the last decade.

It will not be necessary to actively cool a very large IR telescope, nor will its optical components require highly precise figuring. Hence, it should be relatively simple and inexpensive to design and fabricate. It appears possible that passive, radiative cooling could achieve temperatures lower than 200°K with appropriate baffling and shielding from sun, earth and moon. In the Sortie mode shielding by the body of the Shuttle itself would be used. Pre-cooling of the telescope to operating temperature prior to launch, and maintenance of that temperature during launch with suitable insulation, will probably be necessary for relatively short Sortie flights. A large telescope aperture maximizes the signal-to-noise ratio achieved in a given exposure time by instruments used in conjunction with the telescope. Currently available detectors are not background-limited at wavelengths $> 40\ \mu m$. Sensitive heterodyne detection with very narrow bandwidths would not require a cooled telescope and, in fact, might be more easily interfaced with a telescope which is not cooled. Infrared studies of solar system bodies and other objects of high infrared brightness generally do not require cryogenic cooling of telescope surfaces. Thus, this telescope would be a prime instrument for planetary studies, for example.

Innovative use of a Sortie pallet to support a very large primary mirror, use of a collapsible structure to house detectors, secondary mirrors, etc., and reliance on the Shuttle spacecraft to provide a baseline pointing and stability of about 1 arc min would obviate the need for the large and heavy mounting and pointing systems usually associated with telescopes of this size. Two possible configurations are shown in Figures 6 and 9. In Figure 6, the telescope is shown with a 4.2 m off-axis paraboloid primary, mounted perpendicularly to the pallet, with a prime focus inside a Sortie Lab. In Figure 9 a very large 4.2 m x 8.4 m primary rests flat on the pallet and prime-focus instruments are mounted on a structure deployed after the payload bay doors are opened. Many variations on this general approach are possible, including the introduction of Newtonian or modified Coudé foci with appropriate secondary and tertiary mirrors. The primary mirror might be mounted on an invar truss structure, thinly coated with aluminum and polished. The construction of a low weight primary by replica techniques should be possible.

The very large IR telescope is best suited for observations in narrow bandwidths over small fields of view. Auxiliary instruments should include narrow-band infrared spectrometers and an array of infrared detectors for spatial resolution of extended sources. Liquid helium cooling of detectors to $T \leq 4°K$ will be necessary. Programs of observation would emphasize the detection and spectroscopy of molecular emission and, where possible, absorption from interstellar clouds. Forbidden atomic transitions at far-IR wavelengths in the interstellar medium are also of interest. As discussed above, the large IR telescope holds great promise for the angular resolution and spectroscopy of the substructure of H II regions and of galactic nuclei. Photometry and polarimetry of the far-IR continuum from circumstellar dust shells would also be important. Narrow-band spectroscopy of planetary atmospheres over the entire range of infrared wavelengths should reveal the presence of any trace gaseous constituents and would allow the measurement of isotopic ratios. Medium-resolution planetary spectroscopy in the IR would allow detection of surface mineral bands. Isolation of satellites of the outer planets in the field of view of this telescope would allow a search for such absorption bands as the water ice and water vapor signatures near $50\ \mu m$. Synoptic observations of Mars in the $15\ \mu m$ CO_2 band would provide a monitor for gross atmospheric pressure changes.

Solar physics might also profit from use of a very large infrared telescope. The far infrared and submillimeter spectrum of the sun is of great interest for the study of the chromosphere and low corona, especially if high angular resolution (a few arc sec) is available. This applies both to the quiet and to the active sun and has an important bearing on investigations of the structure of the solar magnetic field. Specific instruments designed for ultraviolet and visible solar observations may be too small to achieve the required high angular resolution. Far-infrared observations of the solar chromosphere and low corona with the very large IR telescope could come at the end of a dedicated astronomy mission, at which time the mirror could be heated without compromising the primary mission objectives. It would be necessary to exclude unwanted visible and near-infrared radiation from the focus.

The very large uncooled IR telescope will complete the ensemble of major infrared telescopes, including the LST and the 1.5 m cooled infrared telescope, necessary for a balanced and comprehensive infrared space astronomy program in the 1980's. The Astronomy Working Group recommends its development as a Shuttle Sortie payload. An alternative 3 m-aperture free flying telescope with Shuttle maintenance, similar to but of less precise optical design than the LST, could accomplish some of the research goals of the very large IR telescope, and would have more observing time on orbit than the Shuttle telescope. Problems of maintaining liquid helium temperatures for the detectors for 6-month observing periods would have to be solved. We have emphasized here, however, the necessity of achieving the largest possible telescope aperture and the Shuttle Sortie configurations suggested offer the promise of achieving apertures significantly larger than 3 m.

A Deep-Sky Ultraviolet Survey Telescope

The basic purpose of an ultraviolet sky survey is to provide reference data on the positions of UV sources and approximate UV fluxes for large numbers of celestial objects, by photography of wide fields of view in the sky. In a survey, such as the Palomar Sky Survey, one records point images of stars from which measures of apparent image diameter and density yield data on stellar brightnesses in the wavelength band selected by the optical system. Although such measures are characteristically a factor of five less accurate than photoelectric photometry performed on a one-star-at-a-time basis, it is obvious that the ability to record images of many thousands of stars during a single 15-minute exposure makes the survey immensely more efficient when data of moderate accuracy will suffice. Such data are appropriate for exploratory programs and for statistical studies, since they provide unbiased samples down to the plate limit. The value of such a survey is adequately demonstrated by the great utility of the Palomar Sky Survey for ground-based astronomy in support of observing programs with large optical telescopes and in identifying radio sources, etc. Indeed, the combination of the UV survey with the existing data would provide a powerful discriminant between various classes of astronomical objects. In the long term the program should produce full sky surveys in two ultraviolet bandpasses, to the faintest achievable limiting magnitudes, plus an ultraviolet spectral survey at a classification dispersion. However, for the immediate needs of the LST and other astronomical programs in the 1980's it is imperative that a survey in at least one ultraviolet bandpass, covering selected regions in the sky, be completed at the earliest possible date.

Exploratory studies with broad-band survey data would involve searches for faint OB associations useful in establishing the distance scale within our galaxy, searches for previously unknown windows in the interstellar dust clouds, searches for stars and galaxies of unexpected UV brightness, etc. They would also provide useful source data on special groups of objects, including flare stars, x-ray sources, quasars, pulsars, and peculiar and metallic-line A stars. They might lead to the discovery of new types of objects, as unimagined by us now, as were quasars and pulsars by astronomers of the 1950's. Statistical studies based on a UV direct-imaging survey would include variations in the UV extinction law for interstellar dust from point to point in the galaxy, the frequency of subdwarf B stars at high galactic latitudes, the distribution of UV luminosities of galaxies in clusters of galaxies, the frequency of galaxies with large UV excesses as a function of galaxy form and distance, and the frequency of faint UV companions of red supergiant stars, among others.

In the Palomar Sky Survey one of the two bandpasses was chosen to include the $H\alpha$ line of hydrogen in order that emission from interstellar clouds of gas might be studied, as well as the brightnesses and colors of stars. This study has been very fruitful for the discovery of planetary nebulae, diffuse nebulae, and supernova remnants, for example. Similarily, in the Deep-Sky UV Survey it is proposed that one of the bandpasses be selected especially for studies of the distribution and nature of interstellar dust clouds. A band, centered at 210 nm, would cover a maximum in the interstellar extinction curve and a maximum in the scattering of interstellar radiation. Thus, many regions now known as "dark nebulae" will be seen as bright "reflection nebulae". In many cases, especially when the source of illuminating radiation can be identified, studies of nebular brightnesses will permit detailed measures of dust densities and density distributions which were not possible previously.

It is proposed that the Deep-Sky UV Survey ultimately include an ultraviolet spectral survey with the same kind of telescope as that used for direct imaging, except that an objective grating would be included in the optical system. The spectra of many stars would be recorded on each photograph in the same large areas of sky as in the direct imaging survey, although the limiting magnitude would be considerably brighter. Two types of spectral survey should be considered, one at moderate spectral resolution (0.1 nm), the other at low spectral resolution (10 nm). The moderate resolution survey would be an efficient means to discover objects with anomalous UV spectra, not previously predicted, which would subsequently be studied in more detail by LST. With the much fainter limiting magnitude of the low spectral resolution survey, one could obtain crude UV spectral distributions for faint galaxies, some quasars and active galaxies, as well as many unusual stellar and x-ray sources. Since high energy processes imply large UV fluxes, the UV spectral survey might be a powerful tool for their discovery. Such spectra would also be of value in the study of Lyman-alpha emission of galaxies of moderate redshift.

The basic instrument for the Deep-Sky UV Survey would be an all-reflecting Schmidt camera. Two possible configurations are schematically illustrated in Figure 3. The following telescope characteristics have been suggested:

Aperture:	75 cm
Focal Length:	150 cm
Focal Ratio:	f/2
Plate Scale:	138 arc sec/mm
Field Size:	5 x 5 degrees (13 x 13 cm)
Angular Resolution:	2.8 arc sec (film-limited by 20 μm image element)
Limiting Magnitude:	$m_v \approx 19$ for unreddened B0 stars with direct imaging.
	$m_v \approx 9$ for unreddened B0 stars with objective grating and 0.1 nm spectral resolution
	$m_v \approx 15$ for unreddened B0 stars with objective grating, 10 nm spectral resolution and diminished spectral widening.

The limiting magnitudes cited are for direct photography. An increase in these limits by two or more magnitudes might be realized by use of image tubes.

If one assumes a 5° x 5° field and makes a 10% allowance for field overlap and spacing, roughly 1800 fields would be required to cover the whole sky (41,000

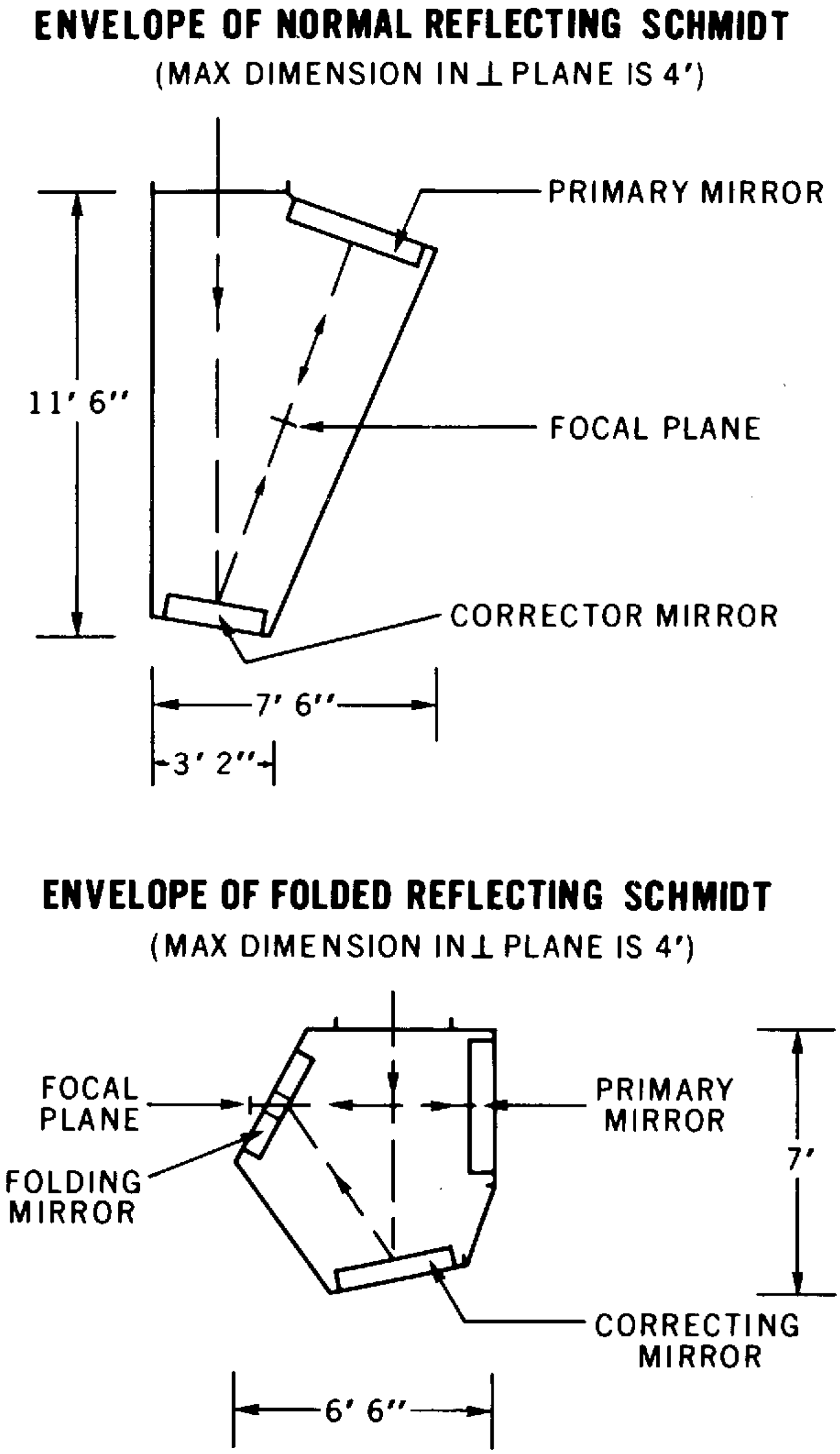


Figure 3. Normal and Folded Reflecting Schmidt Telescopes

square degrees). Orbital geometry for a 90-minute orbital period limits the length of time in the earth's shadow to about 35 minutes. With 15-minute exposures, two fields per orbit, or 32 fields per day, could be photographed. Thus, the total time in orbit required to cover the whole sky would be 57 days. A band of sky 30° wide, extending over 360° of galactic longitude, could be surveyed in 15 days.

The Space Shuttle in the Sortie mode is an ideal vehicle for a project of this kind. The requirements for good angular resolution and wide field of view necessitate the use of photographic emulsions as the basic data recording device. The Shuttle makes film recovery possible. The program can be completed in a reasonable number of Shuttle flights. Manned attendance and operation might permit instrument simplification in some areas, although instrument operation would be largely automatic. Whether more than one telescope could be flown on each mission depends upon a trade-off between resources and efficiency. The telescopes could be gimbal-mounted on a Sortie pallet with possible manned remote control from inside the Shuttle cabin, or a single telescope could be airlock-mounted to a Sortie lab, allowing direct manned access for film handling and other functions. The required airlock aperture would be about 36 inches.

A 1-Meter Diffraction Limited UV-Optical Telescope

An important advantage of the Shuttle Sortie mode for astronomical observations is that it will allow the use of experimental techniques which demand physical return of the data--in particular, the use of photographic film and other high resolution imaging detectors of large dimension. In its programs of high angular resolution imaging the Large Space Telescope will be limited to small fields of view by the maximum size of sensors with remote-readout capability which are expected to be available by 1980. For example, an imaging sensor having a square field of 50 mm and a 50% Modulation Transfer Function at a resolution of 20 line pairs/mm, would view a 36 arc sec field in the sky if matched to the diffraction limited resolution of the LST optics. Research objectives requiring precise imaging at UV-optical wavelengths over relatively wide fields in the sky (say 0.5 degrees), with angular resolution greatly exceeding our ground-based capabilities, could be efficiently accomplished with a second telescope, complementary in nature to the LST--a telescope which would not be limited by the necessity for the remote readout of data. To this end the Astronomy Working Group recommends the development of a 1-meter aperture diffraction limited UV-optical telescope to be flown on Shuttle Sortie missions wherein data could be collected on film, possibly with the aid of electronographic devices, and returned by man to earth. The potential of a Sortie mode 1-meter telescope for precise UV-optical imaging over wide fields of view is enormous and could be realized with existing technology.

The 1-meter UV-optical telescope would also be an excellent instrument for precise intermediate or broad-band photometry of moderately bright objects (say $m_v \lesssim 15$). Although such data might be collected by LST, depending upon whether suitable instrumentation for this purpose is included in the LST-SI, it seems likely that these programs would not be among the primary objectives of that telescope. Owing to the baffling of sunlight by the body of the Shuttle, the 1-meter Sortie telescope could make observations at smaller angles from the sun than will likely be possible with the LST. Finally, but perhaps of greatest importance, a versatile 1-meter UV-optical telescope flown regularly during the 1980's on Shuttle Sortie missions would provide an excellent test facility for instrumentation or high-risk observing programs being considered for the LST.

The basic configuration of the proposed 1 m diffraction-limited telescope is illustrated schematically in Figure 4. It is envisioned as a f/30 Ritchey-Chretian three mirror system with a modified coudé focus inside a Sortie Lab. Conversion to other focal ratios could be done near the image plane. A fork-type mounting would be used with intersecting "declination" and "polar" axes, the latter being parallel to the long axis of the Shuttle (Figure 5). A coudé slot along one side of the telescope would permit optically unobstructed access to about 80% of the available hemisphere of the sky. Image detectors, photometers or spectrographs inside the Sortie Lab could be made to rotate with the image or could be fed through an image de-rotator. Provision would be made for evacuating an instrument chamber at the focal plane. A baseline Shuttle stability of 1 arc min, as might be obtained with control moment gyros, would allow relatively simple fine guidance at the focal plane.

The optical system proposed would provide high-quality images over a field of view $\approx 0.5°$. Angular resolution approaching 0.12 arc sec at 600 nm should be achieved on-axis, with little degradation of this performance over the entire field if a field flattener is used. Because of its small secondary mirror and long focal ratio, the optical system would be optimized for the resolution of fine detail in astronomical images of modest contrast.

Auxiliary instruments for the coudé focus of the 1 m telescope should include relatively conventional ones supplied as part of the total facility. It will be equally important to provide for easy adaptation of special experimental devices for some observers. Standard equipment should include an air-lock chamber surrounding the focal plane, auxiliary optics for field flattening and for near-focus scale conversion to f/10 and to f/3, a photographic film camera, an electronographic camera, an ultraviolet imaging spectrograph, an image-scanning photometer, medium and low resolution spectrometers, and a photometer with high-time-resolution capability. Manned manipulation of these instruments

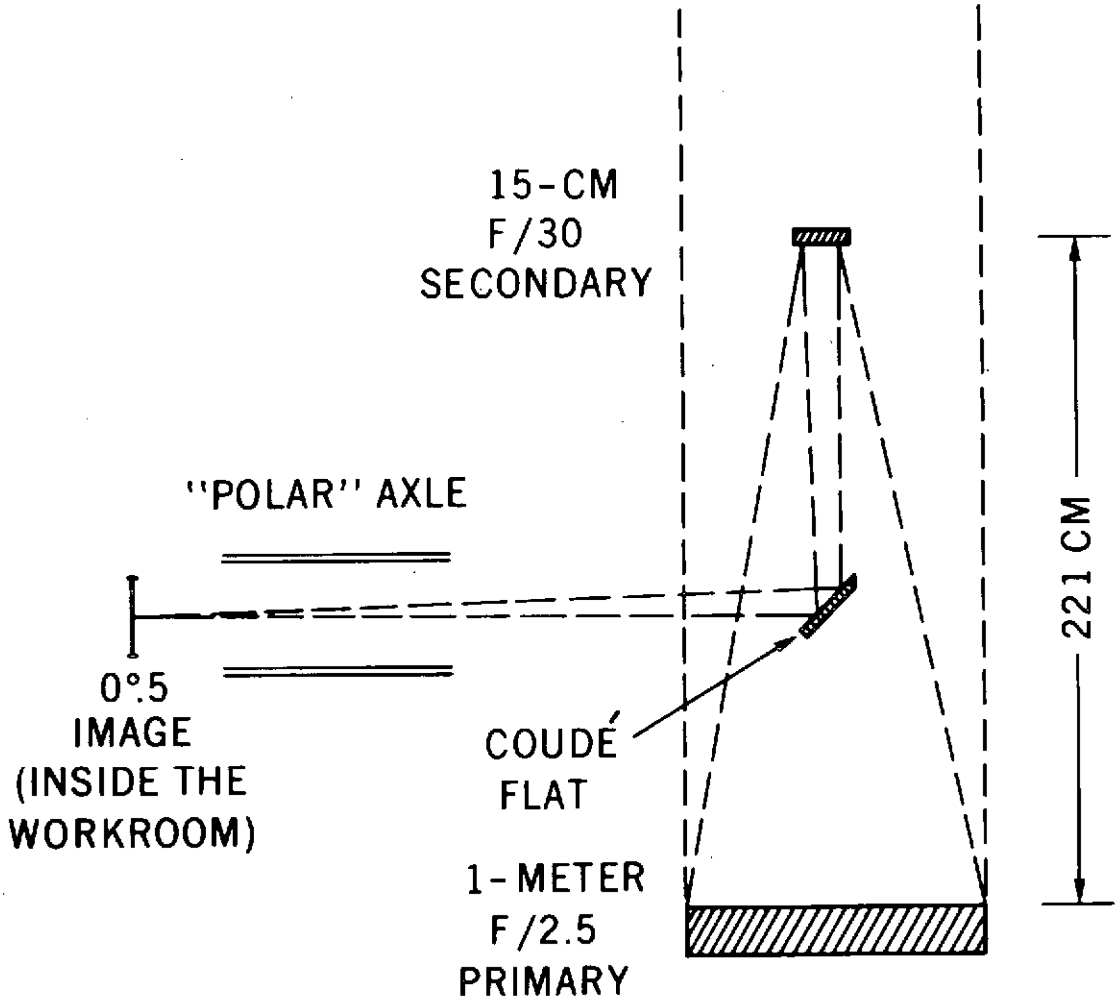


Figure 4. 1-M Diffraction Limited UV-Optical Telescope

will be aided by an ultraviolet image converter system, for image viewing. For polarization studies off-axis foci should be avoided. A small polarimeter could be placed on the optical axis of the 1 m telescope, mounted behind the tertiary mirror. This assembly could be rotated to facilitate polarization measurements.

The 1 m telescope will be of importance in many research areas, including the following: high-spatial resolution imaging of filaments, knots and globules at various UV-optical wavelengths in galactic nebulae; studies of the statistics of dark globules seen against bright nebulae versus foreground stars seen against dark nebulae; resolution of nuclei, distance indicators and structural detail in both normal and peculiar galaxies; high-spatial resolution synoptic imaging of planets for studies of the dynamics, composition and structure of planetary

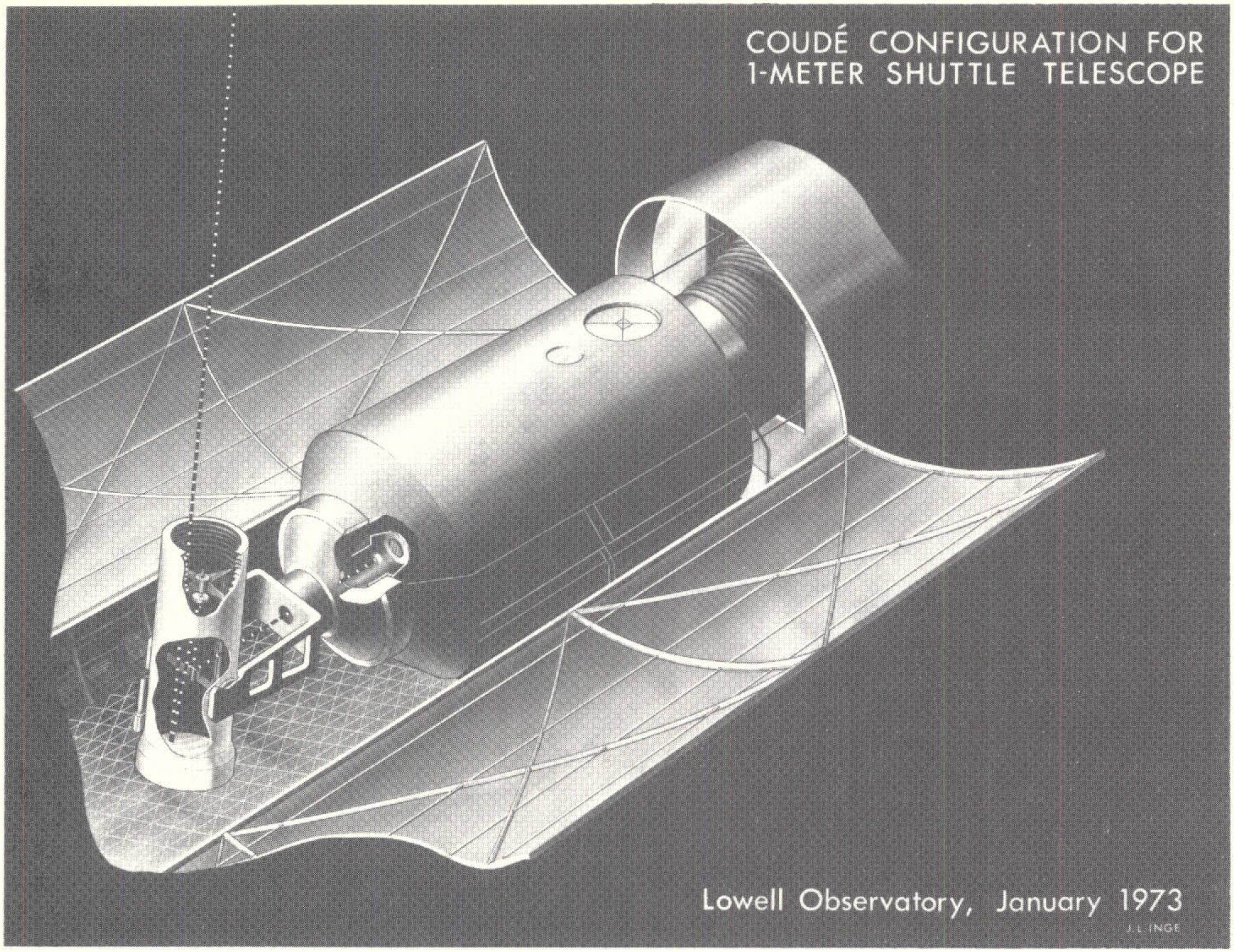


Figure 5. Coudé Configuration for 1-Meter Shuttle Telescope

atmospheres; polarimetry, with high angular resolution, of extended sources; ultraviolet photometry of star clusters for studies of the relative bolometric luminosities of stars, the determination of evolutionary tracks, and the investigation of elemental abundance effects; determination of the magnitude distribution of ultraviolet sources in various directions in our own galaxy; ultraviolet photometric studies of relatively nearby clusters of galaxies to determine their bolometric luminosity functions; carefully calibrated UV-optical flux distribution measurements of stars of intermediate brightness ($m_v = 8^m$ to 15^m) to aid in establishing a network of flux standards for the LST and other telescopes and against which standards stellar population samples might be compared; and statistical sampling of selected sky areas to extend the deep-sky ultraviolet survey.

In a number of these programs the potential for efficient observation of extended objects by the 1 m telescope would be exploited to lay the ground-work for more detailed investigations with the LST. In other programs the 1 m telescope would relieve the LST of the necessity of carrying out observations of moderately bright objects for which a smaller telescope would suffice. In certain programs, notably planetary synoptics, it is highly desirable that the 1 m telescope be flown three times or more per year. It would constitute no more than 1/2 of a Shuttle Sortie payload.

AUTOMATED, FREE-FLYING EXPLORER SATELLITES

A balanced space astronomy program in the era of the Space Shuttle will require an active and on-going Explorer program. Some research objectives will be achievable only with automated, free-flying Explorer satellites, by virtue of the requirement for extended on-orbit observing periods or because of special environmental constraints. In such cases pre-launch checkout in the Shuttle and perhaps even experiment operation in conjunction with a Sortie mission will be desirable. The proposed Lyman Alpha Explorer (LAE) exemplifies this class of free-flying payloads and is discussed in some detail below. A second free-flier of great interest, a Cosmic Background Explorer, is also briefly described.

The Lyman Alpha Explorer

The LAE is intended to observe hydrogen Lα (121.6 nm) emission and, perhaps, also emission at wavelengths near the Lyman discontinuity (91.2 nm) from very faint sources. In near-earth orbits (altitudes $<$ 50,000 km) the earth's bright hydrogen geocorona strongly interferes with such observations. The LAE would operate in heliocentric orbit, at a 1 A.U. solar distance, and about 10^6 km from the earth. It would thus be placed outside the earth's geocorona and be inserted into the interplanetary medium. Initial launch into near-earth orbit on the Shuttle would be followed by final instrument check-out and then launch into solar orbit by a Delta second stage (See Figure 8).

The LAE experiment package would consist of a 0.5-meter aperture telescope instrumented for spectrophotometry at relatively faint light levels over the wavelength range 80 - 135 nm, with a very high spectral resolution capability near Lα. The instrument package would be closely akin to that planned for the International Ultraviolet Explorer (IUE). The conversion of the IUE experiment to meet the requirements of this mission is a topic of future study.

The observational functions of the LAE would include the following:

- Measurements of the weak Lα emission from comets in their early development and late regression phases, when they are relatively far from the sun. These data are relevant to the modeling of the evolutionary history of a comet. Quantitative measurements can classify the type of comet from its activity and can follow the time development of its hydrogen envelope.

- Measurements of the Lα "airglow" of the planets. These data can be examined for average intensity and temporal variations and can be used to infer exospheric temperatures.

- A search for faint Lα emission from late-type stars. Such data are relevant to investigations of stellar chromospheres and coronae.

- Observations of Lα emission from H II regions.

- Examination of the weak backscattered solar Lα from hydrogen in and around the solar system. Data from such mappings could be used to detect asymmetries in the local hydrogen envelope and to determine relative motions between the galactic arm hydrogen and the solar system.

- Examination and mapping of the earth's Lα airglow to establish the boundary of the earth's exosphere and its variations with solar activity.

The Cosmic Background Explorer

This experiment would be designed to survey the spatial and spectral distribution of the cosmic microwave background radiation field, an apparent relic of the "big bang" origin of the universe. The instrument package would include a small ($\lesssim$20 cm aperture) telescope with a 5° field of view, an interference spectrometer and state-of-the-art photoconductive or bolometric detectors. The entire instrument would be cryogenically cooled with liquid helium to below 4.2°K. Since any gas would condense on optical or sensor surfaces at this temperature, the experiment must be flown in a free-flying satellite, well away from the contamination of the spacecraft which launched it, and coarse pointing and stability ($\pm 2°$) must be provided by LHe cold-gas thrusters. Photometric bands over the range 100 μm to 3 mm, wavelengths largely inaccessible from the ground, would be observed. (Further discussion may be found in Appendix A, pages 4-6.)

ADDITIONAL SHUTTLE SORTIE PAYLOADS

"Piggy-Back" Experiments

Space Shuttle Sortie missions, whether dedicated to astronomy or to other disciplines, will offer ample facilities for an abundance of relatively small, rocket-class or Explorer-class experiments. These devices should be essentially self-contained with regard to their pointing and stability, control, and data handling functions, while relying on the Shuttle for power, for basic pointing information, for elementary computer facilities and for telemetry. A small instrument which presents minimum problems of integration into a given payload mix will probably find more flight opportunities than one requiring dedicated attention and resources. Instruments might be mounted in Sortie Laboratory airlocks, allowing direct access, or rigidly on a Sortie pallet, if highly precise pointing or great stability are not required. Telescopes or cameras requiring pointing flexibility with good stability could be mounted on gimbaled pallet platforms. Stabilized platforms providing pointing and stability performance exceeding 1 arc sec, and which also provide an acoustical and thermal buffer between the experiment and the remainder of the Shuttle, appear feasible and should be provided as standard equipment for Sortie missions. By their nature "piggy-back" experiments should be modest in cost and should be conceived and implemented over relatively short time intervals. It is difficult to anticipate the short-term requirements of a large cross-section of the astronomical community a decade hence, and we have not tried to do so in any comprehensive way here. The Working Group considered several small payloads of scientific importance, which typify "piggy-back" experiments. One of these, a very-wide-field galactic camera, is outlined in detail below. Two other small payloads, an astronomical flux calibration package and a polarimetric experiment are discussed briefly.

Very-Wide-Field Galactic Camera— Astronomical instruments, even those designed for sky survey work, are usually confined to rather small fields of view on the sky. The Palomar Sky Survey plates, for example, are 6.6 degrees square. The Deep-Sky UV Survey telescopes suggested above will view $5^\circ \times 5^\circ$ fields. While fields of this size yield relatively high angular resolution they may not directly reveal the large scale distribution of nebulae and stellar clouds in the Milky Way. The now famous Gum Nebula was not recognized as a physical entity until 1952, because of its 90° angular extent. Complex mosaics of small-field photographs present problems in quantitative analysis. For example, in constructing isophotal contours in the galactic plane, one should obtain on the same plate the Milky Way and the extragalactic sky background on both sides. Moreover, for such extended objects, there is a periodic superposition of scattered light from interplanetary dust (zodiacal light and gegenschein), which varies during the course of the year. The separation of the interplanetary and galactic light requires a precise morphology of both phenomena.

The study of large diffuse objects of low surface brightness has attracted considerable interest in recent times. The unique nature of the Gum Nebula has now been recognized and the existence of hotter and younger versions of it, not detectable in visible light, has been proposed. The explanation of the "giant loops" or galactic spurs as supernova remnants may be incorrect. Predictions have been made of the existence of H II regions excited by low-energy cosmic-rays, rather than by hot stars or flashes of radiation from supernovae. We are thus dealing with questions of the primary sources of energy for the interstellar medium and the general state of ionization of interstellar gas.

The proposed Very-Wide-Field Galactic Camera would be used in the investigation of such large scale, faint light phenomena. The sky could be surveyed with fields of view of at least 60 degrees. Narrow-band interference filters would isolate Lyman Alpha, the Mg II λ 280 nm line, the He I λ 1082 nm line and other astrophysically important transitions. Broad ultraviolet band-passes could be utilized for imaging general stellar fields. The camera is envisioned as a larger version of wide field UV cameras that have been flown in sounding rocket payloads or of the wide field camera of Carruthers flown on Apollo 16. It would have an f/1 focal ratio with an aperture $\lesssim 20$ cm. Its sensitivity and angular resolution would exceed those of the rocket cameras because of its larger aperture and the superior stability offered by Shuttle Sortie operations, i.e., ± 1 arc min or better, provided either by Shuttle baseline stability with control moment gyros or by a stabilized pallet platform. Extrapolation of rocket experiment results yields a limiting stellar magnitude $m_v \approx 11$ for O-type stars in a 210 sec exposure. Fainter limits would be achieved with electronographic techniques or longer exposure times. Stellar photometric accuracies would be on the order of ± 0.1 mag.

The proposed observing programs would involve a general sky survey in several ultraviolet and near-infrared bandpasses yielding:

- stellar color-color diagrams and statistics on interstellar extinction.

- isophotal contours of the Milky Way, with detection of the full extension of various stellar populations among the dense stellar clouds of the Galaxy, determination of luminosity functions, studies of diffuse galactic scattering, etc.

- isophotal contours of nearby galaxies (the Magellanic Clouds, M31, etc.), observations of long filaments extending more than 20° from the Large Magellanic Cloud, observations of stellar clouds at high galactic latitudes, searches for intergalactic bridges and intergalactic matter in clusters of galaxies.

- characteristics of scattering by dust in reflection and dark nebulae, as a function of wavelength and geometry in relationship to star clusters.

- morphology of H II regions in the light of important ultraviolet lines.

- data on the distribution and ultraviolet brightness of sources of scattered light in the interplanetary medium.

Astronomical Flux Calibration Payload—These experiments would establish an internally consistent network of standard sources, distributed uniformly around the sky and covering a wide range in apparent brightness. The flux distribution of each object would be calibrated to the highest achievable accuracies over the wavelength range 110 nm to about 1000 μ m. The telescope/spectrometer package would be calibrated against laboratory sources before and after the Sortie mission. It would also be calibrated in orbit by reference to standard sources flown in a subsatellite at distances many kilometers from the Shuttle. The standard source network would provide flux references for LST and other space and ground-based observing programs.

Polarimetric Experiments—A polarimeter capable of observations at ultraviolet and infrared wavelengths in a Shuttle Sortie payload would provide a valuable extension of ground-based polarimetric observations. Consideration should be given both to a telescope designed specifically for polarization measurements and to a polarimeter to be used in conjunction with the 1-meter UV-optical telescope. Scientific goals would include identifying source mechanisms of ultraviolet light in non-stellar objects; determination of grain composition, size and refractive index in circumstellar and interstellar dust, planetary atmospheres and the zodiacal cloud; extension of circular polarization measurements in magnetic white dwarfs to the ultraviolet; studies of spatial polarization structure in small galactic dust clouds and the Crab Nebula; mapping interstellar particle sizes as a function of position in the galaxy; synoptic polarimetry and photometry of Mars between 200 and 400 nm to monitor atmospheric dust content and pressures as a function of season; and polarimetry of the earth's atmosphere as a realistic test of techniques used in planetary studies.

Other Large Experiments

The Astronomy Working Group considered several relatively large Shuttle Sortie Payloads which are of potential importance but which necessarily were discussed in less detail than the major facility telescopes discussed previously. These payloads are summarized briefly below.

An XUV Telescope—A grazing-incidence telescope and instrument package similar to the Low Energy Telescope proposed for High Energy Astronomy Observatory Satellites (HEAO) would be used to observe astronomical sources from soft X-ray wavelengths to as far longward in wavelength as instrumental sensitivity and interstellar extinction will allow, i.e., from about 2 nm to perhaps 50 nm or beyond. An exploratory mission with a small telescope dedicated to the 50-90 nm region should also be considered. Objectives include coronal studies of nearby stars; mapping of discrete and extended XUV sources around the sky; XUV spectral studies of discrete and extended sources; a search for interstellar absorption edges; studies of the distribution of interstellar matter in the immediate neighborhood of the sun; and time variability studies of XUV sources.

Cometary, Condensate and Meteoroid Simulation Experiments—These experiments are pertinent to the development and in situ testing of theories of comet formation and evolution, of condensate behavior in space and of the entry of meteorite debris into the earth's atmosphere. The experiments include the in-orbit release and observation of single and multi-component gases; the in-orbit release and observation of ground-manufactured ices of various size and compositions; propulsion of a synthetic comet beyond the earth's magnetosphere and observation of its evolution; the injection of artificial meteoroids of known properties into the earth's atmosphere with subsequent spectral and photometric observations. The viability of the comparison of such artificial devices to real comets and meteoroids remains to be determined.

Spatial Interferometers—Very high angular resolution ($\approx 10^{-5}$ to 5×10^{-8} radians from 100 μm to 0.5 μm) interferometric observations of relatively faint sources by aperture synthesis would be facilitated in space by the absence of atmospheric scintillation, seeing fluctuations and absorption. The Shuttle baseline of 14 meters could be a first step, although a longer baseline (30 meters or more) would be more satisfactory. The knowledge of the baseline orientation with respect to stars, with an accuracy of a few arc sec, and great baseline stability would be required. Two methods of fringe detection could be used: independent heterodyne detection and IF mixing; or classical Michelson fringe detection, which has the energy advantage of broad bandwidths.

If its feasibility can be established by ground-based studies, such an instrument would be of exceptional scientific importance. This is particularly true at infrared wavelengths, since it is the only possible way to achieve angular resolution comparable to that of the LST at UV-optical wavelengths or to current long baseline radiofrequency interferometers. Important applications would include measurements of stellar angular diameters, of diameters of circumstellar dust shells and of the angular separation of close binary stars, as well as the resolution of substructure in nebulae, galactic nuclei and quasars.

ILLUSTRATIVE ASTRONOMY-DEDICATED SHUTTLE SORTIE MISSIONS

Figures 6 through 9 illustrate four examples of Shuttle Sortie missions dedicated to astronomy. The instruments shown are major facility telescopes plus one free-flying Explorer satellite with its own booster stage. Each major telescope constitutes roughly one-half of a Sortie payload. Each, therefore, is amenable for use on semi-dedicated mission in combination with experiments from other disciplines. However, mutual compatibility of such experiments must be assured. Observations with the major telescopes will require primacy in the control of Shuttle orientation. A small satellite to be launched from the Shuttle as in Figure 8, need not necessarily be an astronomical Explorer. Sharing the payload bay on flights of opportunity with Shuttle-launched free-fliers would be one method of increasing total yearly in-orbit observing time for a given telescope. Manned access to the focal plane of one major telescope, through an airlock in a Sortie Lab, is shown in Figures 6, 7, and 8. Such access though desirable in some cases, is not essential. It might be traded for increased payload size or weight as illustrated in Figure 9. Without the Sortie Lab, pallet instruments might be remotely controlled from inside the Shuttle cabin or from the ground. Utilities, data mangement capability and other facilities normally provided by a Sortie Lab should then be provided on the pallet. Roughly estimated total payload weights range between 43,000 pounds and 48,000 pounds for the four cases illustrated. The contribution of the astronomical instruments and associated support equipment to these total weights ranges from 24,000 pounds to 27,500 pounds.

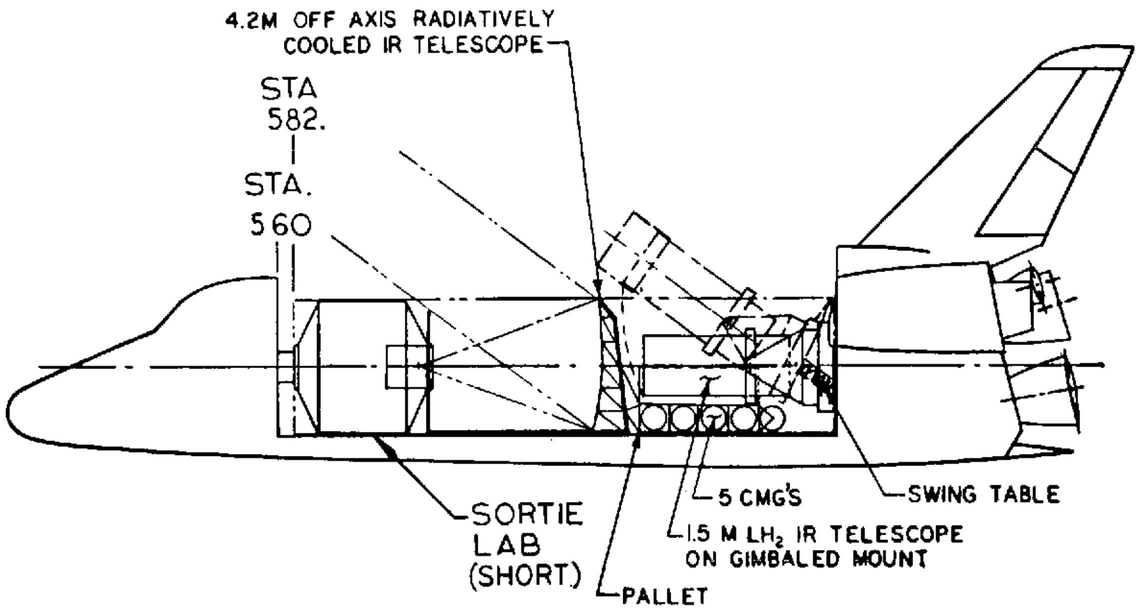


Figure 6. Stellar Astronomy Mission I

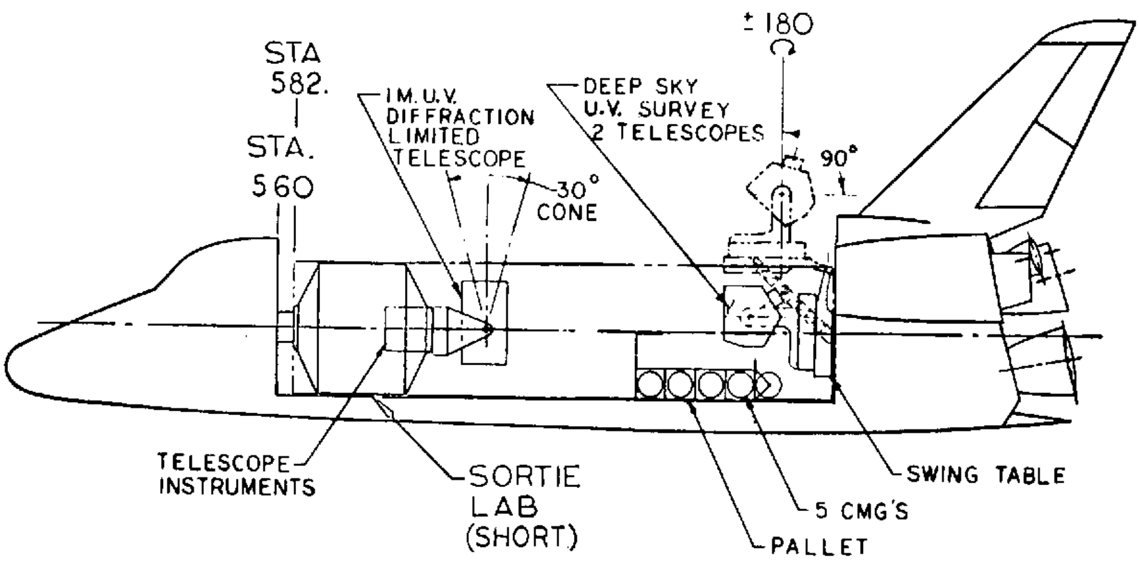
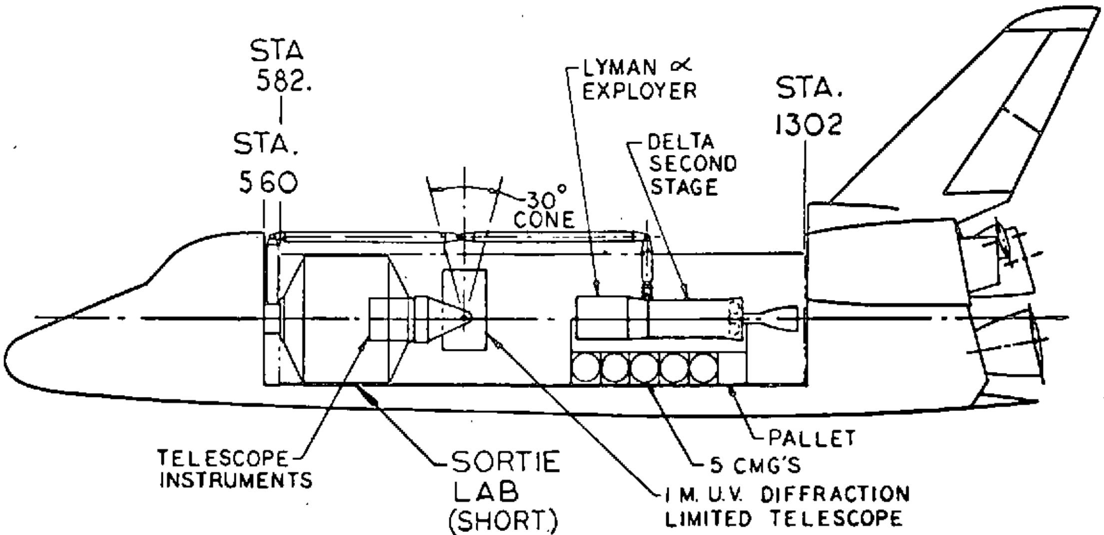
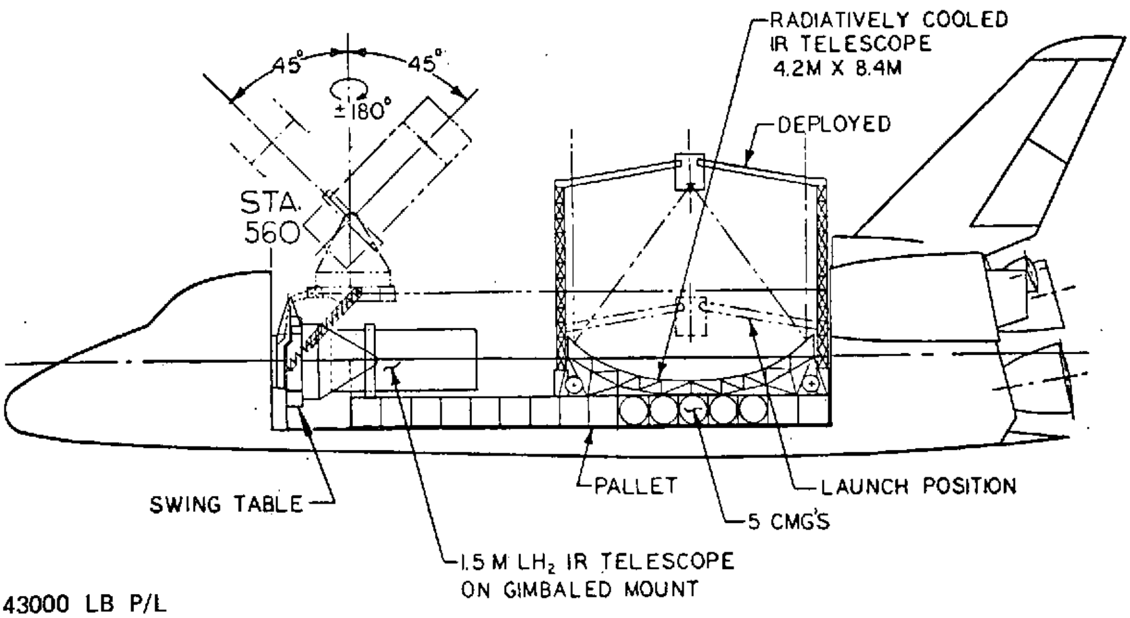


Figure 7. Stellar Astronomy Mission II



44000 LB P/L
(INCL. 24000 LB EXP.)

Figure 8. Stellar Astronomy Mission III



43000 LB P/L
(INCL. 27000 LB EXP.)

Figure 9. Stellar Astronomy Mission IV

A SUGGESTED SPACE ASTRONOMY MISSION MODEL, 1980-1991

The major facility telescopes discussed previously are denoted as "major" instruments not only because of their size, weight, complexity and likely cost but also because of their probable high level of interest to the astronomical community. If they are to be of real value, however, they must be usable during the maximum feasible in-orbit observing time. Comparable telescopes at ground-based observatories are frequently used more than 200 nights per year. One possibility is that most of the major instruments be flown in free-flying satellites with periodic Shuttle maintenance. This is the clear choice for the LST, for example. However, good reasons exist for using the other facility instruments in the Shuttle Sortie mode, as has already been discussed in relation to each instrument. It is the opinion of the Astronomy Working Group that a minimum of two and preferably three astronomy-dedicated Sortie missions per year, in addition to flights of opportunity with other disciplines or with Shuttle-launched free-flying satellites, will be necessary if the research potential of these instruments is to be fully realized. In addition, it is our opinion that Sortie missions substantially longer than 7 days will frequently be required and that the option of mission durations up to 30 days should be made available at the earliest possible time.

The suggested mission model in Table 2 reflects these points of view. It is assumed here that the number of Sortie flights per year will not reach an equilibrium value until 1985. We recommend that the few Sortie flight opportunities likely to be available during the early 1980's be used to implement the research program of the 1.5 m Cooled Infrared Telescope and the Very Large Uncooled Infrared Telescope. Development of these instruments should therefore begin in the latter half of the present decade. The mission model includes flights of an XUV telescope primarily because that telescope exemplifies in size and complexity the kind of major instrument which might be phased into astronomical Sortie payloads as the Deep-Sky UV Survey draws to a close. Sortie missions involving major facility telescopes are denoted as follows:

IR Sortie	—	1.5 m Cooled Infrared Telescope + Very Large Uncooled Infrared Telescope
UV Sortie #1	—	1 m Diffraction Limited UV-Optical Telescope + Deep-Sky UV Survey Telescope
UV Sortie #2	—	1 m Diffraction Limited UV-Optical Telescope + XUV Telescope

Table 2

Astronomy Missions, 1980 - 1991

	80	81	82	83	84	85	86	87	88	89	90	91
IR Sortie	$\frac{1}{2}$	$\frac{1}{2}$	1	1	1	1						
UV Sortie #1					1	1+1*	1*		1*			1*
UV Sortie #2							1	1*	1*	1*	1*	1*
UV/IR Sortie #1								1*	1*	1*	1*	1*
UV/IR Sortie #2							1	1*	1*	1*	1*	1*
"Piggy-Back" Instruments Explorer-Class			1	1	2	1	2	1	2	1	2	1
"Piggy-Back" Instruments Rocket-Class			5	8	10	10	10	10	10	10	10	10
LST	Launch In 1980 with Regular Revisits Thereafter.											
Automated Exporers		1		1			1			1		1

*30-Day Missions

UV/IR Sortie #1 — 1 m Diffraction Limited UV-Optical Telescope + Very Large Uncooled Infrared Telescope

UV/IR Sortie #2 — 1 m Diffraction Limited UV-Optical Telescope + 1.5 m Cooled Infrared Telescope

The IR Sortie missions shown in 1980 and 1981 are semi-dedicated flights of the 1.5 m Cooled Infrared Telescope, made in conjunction with an experiment from another discipline.

THE IMPACT OF ASTRONOMY ON THE SPACE SHUTTLE PROGRAM

Some aspects of the program of space astronomy discussed in previous sections will affect Shuttle and Sortie Lab design and operations or will in other ways have an impact on the Shuttle program. These are discussed below.

ROLE OF THE SCIENTIST IN SPACE

In addition to two pilots and one mission specialist, the Shuttle will provide facilities for from one to seven other crew members. It is essential that these crew members be scientists, with professional competence to make value judgments pertaining to the scientific goals of the mission and with an intimate familiarity with the instrumentation. Special training will enable them to evaluate the interaction of spacecraft systems and mission requirements with the scientific objectives and to effect changes either before a flight or in orbit to optimize the Shuttle-telescope interfaces. They may or may not be "principal investigators" in the sense that they exercise final command over the scientific program or the telescopes. However, they should be drawn from the scientific community and have a direct personal interest in the analysis and publication of the observational results. It should be stressed that the presence of scientists as members of the crew in no way removes the need for adequate communications with the ground. "Quick-look" analysis of data will sometimes suggest modifications to an observing program. Such changes to a carefully considered plan should be based on consultations with a scientific team on the ground, having access to large computers, to the scientific literature and to the scientific community at large. We also recommend that the "mission specialist" possess a scientific background, preferably in astronomy for astronomical missions. He could be a scientist-astronaut.

MANNED ACCESS TO INSTRUMENTATION

Direct manned access to the focal planes of major instruments on Sortie missions would be useful for certain functions such as interchange of auxiliary instruments; manual film handling; verification of field of view, instrumental alignment and focus; simple repairs or replacement of failed components. However, some of these functions could be performed remotely, perhaps by an observer in the Shuttle cabin. We do not consider the direct involvement of man with the major instruments during the course of in-orbit operations to be vital to Shuttle astronomy. Man's major role will be to react to contingencies, to quickly evaluate data and to implement changes in observing procedures as the data require. Such functions will require major expertise on the ground during a mission and excellent communications between ground-based scientists and the experiment operators in the Shuttle. An experiment crew of at least four, in addition to pilot and co-pilot, is recommended.

PAYLOAD BAY CONFIGURATION

Astronomical Sortie missions will require two possible payload bay configurations, a pallet plus a small Sortie Lab or, less frequently, a pallet only. We view the small Sortie Lab as providing utilities, data management facilities, communications, space for consoles or a small computer for the control of pallet instruments, and focal plane access to an instrument if required. In addition, the Sortie Lab will probably simplify interfacing between an experiment payload and the Shuttle itself.

DATA AND COMMUNICATIONS

A continuous, experiment-dedicated, voice link between scientific personnel on the Shuttle and ground-based colleagues is desirable, but voice contact for an average of 15 minutes per orbit is required. A 256 Kbps data down-link for 10 minutes per orbit is required but transmissions of at least 10 times this rate may be desirable by the 1980's. Picture transmission of at least two pictures per orbit is necessary. A Telemetry Data Relay Satellite, allowing real time upward transmission of control commands, voice, and pictures and continuous downward data transmission, is highly recommended.

POINTING AND STABILIZATION

Astronomy will require dedicated Shuttle pointing and accurate pointing information. Baseline pointing and stabilization near ± 1 arc min are highly desirable for most astronomy payloads and will be essential for the very large, uncooled infrared telescope. This requirement, as well as the stringent need for minimal contamination from Shuttle effluents, may be met by use of control moment gyros, momentum wheels, etc., provided as part of the payload if necessary.

CONTAMINATION

Contamination of astronomical experiments on the Space Shuttle can be divided into three categories:

1. The introduction of an artificial atmosphere around the spacecraft
2. Condensation of material on optical surfaces
3. "Artificial stars" produced by small particles of dust from the spacecraft.

Rough guidelines for these categories after day #2 in orbit, are as follows:

Category (1):

All absorption lines, UV, optical and IR, shall be optically thin. Possible exceptions would be lines such as Lα which exist naturally in the earth's upper atmosphere. Continuum emission or scattering shall not exceed 20th mag in the UV in a 1 arc sec circle, or 10^{-16} w Noise Equivalent Power in a 10 arc sec circle (1 m telescope) for $\Delta\lambda/\lambda = 0.5$ bandwidth in the IR at wavelengths from 10 to a few hundred μm.

Category (2):

Less than 1% loss due to absorption of radiation, $\Delta\lambda/\lambda = 0.1$, by condensables on optical surfaces (UV, optical, and IR) for the entire mission.

Category (3):

Less than one "artificial star" (i.e. 10 σ event above 10^{-16} w/ $\sqrt{\mathrm{Hz}}$ as seen by the detector for $\Delta\lambda/\lambda = 0.5$ bandwidth, 10 arc sec circle, and 1 m telescope from 10 to a few hundred μm wavelength in the IR) per orbit.

ACOUSTICAL LEVELS

The dynamic acoustic pressure environment of the Shuttle payload bay during launch is presently listed at a level of 145 db. Initial impressions are that such a level may be inordinately severe and could damage delicate electronic sensors and optical alignments. The launch environments of the OAO's, the Mariners, and the Apollo SIM bay should be examined for the determination of acceptable levels and deviations of acoustical pressures.

FILM AND TAPE STORAGE

Three problems must be considered:

- Prevention of film fogging due to Van Allen belt radiation
- The volume required for film and tape storage for mission lengths up to 30 days
- Prevention of accidental erasure of magnetic data tapes.

Studies of film fogging for Skylab indicate that the high sensitivity ultraviolet film, Kodak 101, can be effectively shielded from the ambient radiation fields for a 235 nautical mile orbit by aluminum of thickness 3 cm for intervals up to 30 days. It is probable that such shielding will suffice for all foreseeable types of film. With regard to film storage volume, we consider a demanding case--that of the Deep-Sky UV Survey cameras. One camera consumes about 1000 frames in 30 days. Assuming an 8 x 8 inch film format, this requires a 660 foot spool of film. With normal winding we would then have a spool about one foot in diameter and 8 inches wide. With shielding included, a film magazine for this spool will require a volume of about 2.5 ft^3. If "rails" are required to prevent film abrasion, this volume will be more than doubled. In the latter case the film supply for each camera should be divided between two magazines with a provision for exchanging magazines during missions. Mu-metal boxes should be provided for tape storage.

SORTIE LAB COMPUTERS

Nova-class computers with a one μsec add time and 16K memories (16 bit words) should suffice. Disk storage of programs is preferred.

PAYLOAD WEIGHT

The astronomical program total payload landing weights may range between 40,000 and 50,000 pounds.

MISSION TIMING AND DURATION

The choice of launch season will be necessary for some astronomical missions. Sortie mission durations as long as 30 days are highly desirable for our major facility telescopes and should be provided at the earliest possible date. The cost effectiveness of these general purpose instruments will always be enhanced by the longest missions feasible at any time.

SUPPORTING RESEARCH AND TECHNOLOGY

The areas which follow, relevant to the space astronomy program outlined here, require developmental work. Relative priorities have not been assigned and the feasibility of each project remains to be established. The areas listed were suggested by individual panel members and have not been discussed by the Working Group as a whole.

CRYOGENIC SYSTEMS

Storage and use of subcritical liquid hydrogen, solid hydrogen, liquid helium, etc., in a zero gravity environment; a large aperture (2 meters) dewar allowing cryogen storage at $T \lesssim 20^\circ K$ for up to 35 days in orbit; long-lifetime (3 - 6 months) cryogen storage systems for automated satellites.

INFRARED TELESCOPES

Low emissivity designs; low emissivity coatings; multilayer coatings for the far-IR; replica techniques for fabrication of large, light weight mirrors; baffling of cooled and uncooled telescopes from solar, lunar and terrestrial radiation; signal modulation techniques.

INFRARED INSTRUMENTS

Imaging systems (multi-detector arrays, image converters, etc.); improved detectors (e.g. photon counting) for wavelengths > 25 μm; improved narrow band, high transmission filters; Michelson interferometers; Fabry-Perot interferometers for 20 - 200 μm; Fourier transform spectrometers; heterodyne detectors.

FAR-INFRARED AND MILLIMETER WAVE INSTRUMENTS

Systematic development of radio-type receivers with improvements in sensitivity by many orders of magnitude; point contact and Schottky barrier diodes, Josephson mixers; local oscillators (coherent sources, possibly gas lasers).

ULTRAVIOLET AND OPTICAL INSTRUMENTS

Electronic imaging systems of large dimensions (>100 mm), high linear resolution, wide wavelength range and remote-readout capability (low noise Si vidicon with good UV response, charge-coupled devices, channel plates for array-sensing plus a photocathode to extend capabilities to wavelengths > 150 nm, uniform high-yield photocathode materials); thin film, alkali metal filters for wavelengths 100 - 300 nm; uses, yields and degradation of ultraviolet phosphors; very large electronographic detectors (up to 8 x 8 inches); film transport system for ultraviolet survey telescopes; gratings with high ultraviolet efficiency; concave echelle gratings; interferometers for high angular resolution measurements in orbit; flux calibration standards for use in orbit.

TELESCOPE POINTING AND STABILIZATION

Internal secondary stabilization systems; gimbal mounts for pallet telescopes (1500 kg of instruments, 0.1 arc sec pointing accuracy and stability, EVA servicing); gimbal mounts for continuous manned access to the focal plane within a Sortie Lab; combination of control moment gyro and momentum wheel systems for attitude control of Sortie Lab.

ORBITAL ENVIRONMENT

Minimization of Shuttle contaminants and their impact on observing programs; definition of acceptable contamination levels for astronomical payloads; dynamics of contaminant effluents near a spacecraft; instruments to monitor contaminants and to determine their effects on optical systems; natural airglow studies above satellite altitudes, especially near 100 μm wavelength (are the Markov bands real?); minimization of effects of Van Allen radiation belts and South Atlantic Anomaly on electronic detectors and on film.

ORBITAL OPERATIONS

System for developing photographic test exposures in orbit; evaluation of telescope/detector performance under conditions of use; preprocessing of data by Sortie Lab computers and associated telemetry; concepts for "quick look" science for astronomers on board the Shuttle (data readout systems, etc.); total requirements for on-board computers.

ADDITIONAL SCIENTIFIC SUPPORT

Continued support of ground-based, airplane, balloon and rocket observations; molecular spectroscopy to generate a computer atlas of interesting transitions in CH_4, NH_3, etc.; improved laboratory flux calibration techniques and primary standards; experiment modeling, time and motion studies for several Sortie observing programs with model instrument configurations.

APPENDIX A

SPACE EXPERIMENTS IN RELATIVITY

RELATIVITY SUBPANEL
ASTRONOMY WORKING GROUP
SPACE SHUTTLE PROGRAM

ASTRONOMY WORKING GROUP
RELATIVITY SUBPANEL

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APPENDIX A

SPACE EXPERIMENTS IN RELATIVITY

INTRODUCTION

The subpanel on relativity experiments was established early in March 1973. The time available to define gravitational experiments and for preparation of the final report was less than one month. A telephone conference was held on March 6, 1973, and a meeting of the panel occurred on March 29, 1973, at National Aeronautics and Space Administration (NASA) Headquarters.

The goal of the panel effort was to identify relativity experiments for the 1980's and the utilization of the Space Shuttle for these experiments.

Gravitation is one of the basic, as well as the weakest, interactions in nature. Although gravity does not appear to play a direct role in microphysics, it becomes the dominant interaction as the scale of the phenomena increases, gaining in influence from stellar to galactic and ultimately cosmological dimensions. Newtonian gravitation is a remarkable description of the gravitational interaction, but it does not comprise a complete theory of gravitation. It is not relativistically invariant nor does it lead to a basic understanding of gravity. The Newtonian description must break down when the dimensionless quantity ϕ/c^2 (ϕ: Newtonian potential; c: velocity of light) begins to approach unity. In our immediate neighborhood, ϕ/c^2 is extremely small: at the earth's surface $\sim 10^{-9}$, on Jupiter $\sim 10^{-8}$, and on the surface of the sun $\sim 10^{-6}$. Because of these small values, the measurement of Post-Newtonian effects is difficult, but nevertheless crucial to a development of relativistic theories of gravitation which are needed to describe the physics of extremely dense matter, gravitational radiation, and cosmology.

Many relativistic theories of gravitation have been proposed. They range from scalar to vector and higher order tensor theories. Of these, the Einstein Theory of General Relativity is the most complete and presently accepted theory. However, it is based on weak and incomplete experimental evidence. Gravitation is in a unique and decidedly uncomfortable situation in that the crucial interplay between experiment and observation with theory, so essential to the development of an understanding of nature, has been marginal at best. This is not the fault of the experimenters, but rather the result of the extremely small magnitudes of the Post-Newtonian effects that can be observed in the gravitational fields available to us.

With every new technological and scientific advance, the prospects for engaging in precision experiments and observations of the gravitational interaction are reassessed. For example, the Mössbauer effect permitted the measurement of the gravitational redshift. The development of low-noise receivers, powerful microwave sources, and large antennas has made the relativistic time delay experiments possible. The discovery of the quasi-stellar radio sources and the application of radio interferometers has allowed a measurement of the relativistic bending of light. It seems that gravitation research in space, although it has not yet been exploited, should also be able to make a major impact on the observational evidence for gravitational theories.

There are four issues in gravitation which would benefit from observation and experiments in space. They are:

- Cosmology.
- Tests to distinguish relativistic theories of gravitation as well as measurements of new gravitational effects.
- Improved "null" experiments to test fundamental principles.
- Search for gravitational radiation.

COSMOLOGY

The basic aim of cosmological studies is to detect and interpret radiation coming from deep space in order to learn about the structure and evolution of the universe. The panel was unanimous in view that cosmology would be the most exciting and important aspect of research in general relativity in the next decade.

Many cosmologically interesting experiments will become possible with telescopes and detectors of the type already being planned for space; the main advantages of which are wider spectral range, higher resolution, and lower sky brightness. For example, the Large Space Telescope (LST) will allow the study of galaxies of substantially increased redshift where curvature effects of the universe should be sufficient to allow tests of the various cosmological models. It may become possible to measure the following three classical cosmological observables: the acceleration parameter of general cosmological expansion, the number of galaxies per unit coordinate volume, and the non-Euclidean change in angular size of galaxies with distance. Quasars will be observable over a much larger magnitude range (down to 26th magnitude) which, coupled with their large redshift, may permit still deeper probing of the universe. None of these cosmological problems have so far proved solvable from the ground. Space-borne instruments will likewise allow studies of the evolution of chemical abundances to far earlier epochs, and perhaps settle the question of when galaxies, quasars, and discrete radio sources actually formed.

Observations with low angular resolution (background) with small, sensitive instruments are of great interest to cosmology. Besides the 2.7°K microwave background (discussed separately), the infrared, X-ray, and gamma-ray background fluxes are of great cosmological interest. Most cosmological theories predict emission of broadband radiation at various stages and the spectrum and flux would reflect which processes were at work. For example, studies of the X-ray background may well shed light upon physical conditions in intergalactic space; a matter of considerable cosmological interest. Measurements of the background radiation at all wavelengths is important in determining the mass distribution and structure of the universe.

Although they do not fall strictly into the category of cosmological studies, it is perhaps worthwhile to note here that there are many other types of space observations which are of great importance to general relativity. Examples are far-infrared studies of galactic nuclei, which very probably owe their vast energy output to gravitation, X-ray observations of neutron stars and black holes in both of which general relativity effects are crucial, and studies of close binary systems, especially in regards to the effects of gravitational radiation.

In short the general relativity subpanel strongly endorses a program of astronomical observations especially of a cosmological nature as probably the most productive area of relativity research in the 1980's. (Some of the above subjects have been discussed in more detail by other panels of the Working Group.)

2.7°K BLACKBODY RADIATION:

If the background radiation is a remnant of an early hot phase of the universe, it will rank along with Hubble's discovery of the recession of the galaxies as one of the most important cosmological observables. The early history of the universe may be written in the spectrum and spatial distribution of this radiation.

Spectrum

There now exist at least 15 ground-based measurements of the spectrum of the background radiation from 73.5 cm to 0.3 cm which yield equivalent blackbody temperatures ranging between 3.7 to 2°K. In this spectral region, the spectrum obeys a ν^2 dependence and even shows the appropriate departure from the Rayleigh-Jeans distribution to a Planck distribution at the points with wavelengths shorter than 0.8 cm.

The situation in the region above 0.3 cm, the far-infrared where a blackbody at 3°K has its maximum power, is not as good as at lower frequencies.

Aside from the point at 0.38 cm derived from interstellar CN absorption, the data do not provide very tight limits to the background radiation. It is now clear that the spectrum is not a gray body spectrum that matched the ν^2 dependence at low frequencies, nor is the data consistent with a Bremsstrahlung spectrum. There does appear to be a peak between 4 and 0.8 cm, and it is certainly true that the data are consistent with a blackbody spectrum of 2.7 ± 0.2°K.

Given the dismal state of far-infrared detector technology, the high frequency results probably reflect the best that can be done at this time from balloon and rocket platforms. The rocket measurements are plagued by short observation times. The background radiation signal, even in the large spectral bandwidths that have been used, is barely visible over the detector and system noise in the short time available. Balloon platforms have the advantage of long observation times but are troubled by atmospheric emission by ozone and water. At an altitude of 44 km, the atmospheric radiation is still 30 times stronger than that from a 2.7°K blackbody in the region between 12 cm^{-1} and 20 cm^{-1}.

Measurements of the spectrum, especially above 12 cm^{-1}, are now a logical candidate for space platforms. Cryogenics in space, although not yet attempted, do not pose any deep problems. A small instrument, less than 75 kg, containing a liquid helium cooled polarizing Michelson or Lamellar grating Fourier transform spectrometer of moderate resolution, say 0.1 cm, with existing detectors and a lifetime of several months would make a major improvement in our knowledge of the background radiation. Such an instrument could be launched from the Shuttle, or for that matter, by many other launch vehicles.

Isotropy

Anisotropies in the radiation may be caused by several effects. A large angular scale anisotropy is expected due to the peculiar motion of the solar system relative to the co-moving frame in which the background radiation may appear isotropic. Indeed the cosmic background radiation may offer a reference frame to allow us to determine our motion. Also, large angular scale anisotropies would occur if the universe experienced an asymmetric expansion. Medium to small scale anisotropies may be the result of density inhomogeneities in the primordial plasma related to the birth of galaxies.

Ground-based and balloon-borne radiometers have, at best, marginally detected the anisotropy of the background radation due to the motion of the earth relative to the source of radiation. The main problems are atmospheric noise, man-made interference, limited sky coverage, and limited integration time (from balloons). There are definite advances yet possible in these experiments, and several groups are trying various approaches to overcoming the problems. Surely some improvements are forthcoming.

Even so, a case can be made for attempting this experiment from space. There are several approaches one could take depending on the availability of liquid helium, pointing capability, power, etc. As an illustration, one approach might be a simple Dicke radiometer operating at about 35 GHz measuring the temperature difference between two horns pointing 90° apart in the sky. Such an apparatus could be small, lightweight, and reliable. Little or no maintenance would be required; some simple on-station tests to check for systematic effects would be desirable. Long integration time, good sky coverage, elimination of atmospheric noise, and better r.f.i. control would be the main advantages of doing this experiment in space.

TESTS OF RELATIVISTIC GRAVITATIONAL THEORIES

The experimental basis for Einstein's General Theory of Relativity is weak and incomplete. Furthermore, it is possible to construct alternate relativistic gravitational theories, as for example, the Brans-Dicke Scalar Tensor Theory, which have a Newtonian limit for weak fields but that make substantially different predictions for Post-Newtonian phenomena. Therefore, improved and new tests of Post-Newtonian effects are necessary. Some experiments provide a test to the first order in ϕ/c^2, while other experiments offer a test to the second order in ϕ/c^2.

EXPERIMENTAL TESTS TO THE FIRST ORDER IN ϕ/c^2

Relativistic Time Delay

Measurements of the relativistic corrections to the travel time of light near the sun, the relativistic time delay, have been made at ground-based installations using radar reflections from planets and radio tracking of deep-space probes. These experiments will continue. Use of multiple frequency transmission (to reduce disturbances caused by the solar corona), long-lived planetary orbiters, and improved ground radar instrumentation may result in 1% accuracy by the end of this decade.

One proposed satellite experiment would use a laser transponder to reduce solar corona effects (see drag-free satellite).

Light Deflection

Efforts will continue to measure deflection of electromagnetic waves in the gravitational field of the sun using ground-based radio interferometers at several frequencies by looking at celestial radio sources. It can be expected that improvements in instrumentation and continued measurements may eventually yield a 1% accuracy.

The classical experiment to detect the bending of light near the sun is, in some ways, an attractive possibility for a space platform. The multitude of problems associated with the atmosphere, eclipse conditions, and short observing time are eliminated. On the other hand, one is still faced with the problems of systematic errors associated with mechanical and thermal stability of the optical system. Control exposures of the undeflected star field must necessarily be made a few days before and after the solar exposure. Precision pointing is required for short periods of time.

The experimental problems lie mainly in the multitude of opportunities for systematic errors, but careful design and control of the experiment might overcome them.

The ever improving accuracy of ground-based radio measurements of light deflection do, to some extent, dilute the importance of this experiment. However, those too are subject to systematic errors which are difficult to evaluate. We clearly benefit from as many independent tests of this important effect as can be made at the 1% level. In principle, optical light deflection is of this accuracy.

Geodetic Gyroscope Precession

The virtually force-free environment of a drag-free space probe offers unique opportunities for experiments to measure new Post-Newtonian gravitational effects. An important experiment to measure four-dimensional curvature is the measurement of the precession of the spin angular momentum of a gyroscope as it makes a closed orbit around a gravitational source - the geodetic precession.

An experiment is being developed by Stanford University to measure the precession of very stable cryogenic gyros in an earth-orbiting satellite. For a circular polar orbit of 500 nautical miles, the geodetic precession is about 6.3 arc sec/year. It is anticipated that a simplified version of this experiment can be flown before the Shuttle becomes operational. This first flight would measure only the geodetic precession, while the final experiment would attempt to measure the geodetic precession with a higher accuracy and also the much smaller Lense-Thirring effect. The gyroscope satellite has to be a drag-free spacecraft

(10^{-10}g) and could be put into orbit by the Shuttle. A technology flight on a Sortie mission to test the experiment system in a low-g environment would be very beneficial if not a requirement.

The experiment package containing the cryogenic gyroscopes and a star-tracking telescope will be enclosed in a liquid helium dewar. The spacecraft for the final experiment would have a weight of about 600 kg (1,320 lbs) and a cylindrical shape of about 2 x 3.6 m (7 x 12 ft.). A circular polar orbit of 930 km (500 n. mi.) would be highly desirable but is not an absolute requirement.

SECOND ORDER TESTS IN ϕ/c^2

A major effort should go into precision measurements of the orbital parameters of planets, asteroids, or drag-free artificial satellites of the sun to determine the Post-Newtonian corrections to their equations of motion. Measurements of the perihelion rotation of fast moving objects offer tests of relativistic gravitational theories to second order in ϕ/c^2. Precision measurements of the orbital parameters of objects with different orbital radii or inclination to the rotation axis of the sun may give a better estimate than we now have for the gravitational quadrupole moment of the sun.

Drag-Free Satellite

The European Space Research Organization (ESRO) has performed a feasibility study of a drag-free satellite in orbit around the sun (SOREL project). The aim of this mission is to make a precise determination of the orbit and at the same time perform a relativistic time delay measurement with laser signals. The mission would provide very accurate measurements of first and second order effects including solar oblateness. The satellite would be launched into a highly eccentric solar orbit with close approach to the sun (eccentricity: 0.588; perihelion distance: 0.28 AU). An onboard laser system in conjunction with an atomic clock would provide time delay measurements and accurate orbit determination. A drag-free control system would reduce random spacecraft accelerations to 10^{-12} m/sec^2 or less to obtain a purely gravitational orbit. The size of the essentially cylindrical spacecraft would be 2.6 x 4.5 m (8.5 x 14.7 ft.) with a mass of 320 kg (700 lbs).

Precision Orbit Measurements (ground-based)

Ground-based radar measurements will give improved planetary orbit determination in the solar system during the coming years. With increased accuracy of orbital data, Post-Newtonian effects on planetary orbits should become more visible.

Solar Oblateness

Ground-based measurements indicate that the sun has an optical quadrupole moment, and one interpretation of this is that a rapidly rotating core is producing a solar gravitational quadrupole. If so, the agreement between the observed and the predicted precession of Mercury's perihelion is fortuitous, and either the observations are in error or general relativity theory needs modification.

The observations of the optical oblateness seem convincing; most of the debate concerns the interpretation in terms of a gravitational quadrupole, rather than surface stresses. The interpretation would be helped greatly if more data over an extended period of time could be obtained. Unfortunately, ground-based observations are seriously hampered by daytime seeing, atmospheric refraction and the limited observing season.

One attractive possibility is a specially designed camera carried into space and operated by an astronaut from earth orbit. Simple calibration procedures can be used to remove lens and emulsion distortion.

Second Order Gravitational Redshift

The development of a space qualified hydrogen maser for the suborbital measurement of the gravitational redshift, to be flown in late 1974, brings up the possibility of using these masers for a second order test of relativistic gravitational theories. A clock placed in an eccentric orbit about the sun with a perihelion of the order of 0.1 AU may be able to determine β independently to 10%. Such an experiment might become part of the drag-free satellite mission.

LENSE-THIRRING EFFECT

A gyro experiment may also demonstrate the gravitational induction field due to moving mass - "magnetic" gravitational fields, the Lense-Thirring effect. The measurement of this effect would be extremely interesting. The magnitude of the Lense-Thirring gyro precession is very small (0.05 arc sec per year for a 500 n.mi. polar orbit) and will require extremely stable gyroscopes.

This experiment could be combined with the measurement of the geodetic precession by using an additional set of gyros in an earth-orbiting satellite.

TEST OF FUNDAMENTAL PRINCIPLES

Gravitation theory rests ultimately on the assumption that the laws of physics, including numerical content, are the same in all inertial frames of reference - the Strong Equivalence Principle. Space flight offers us access to reference frames of a variety not yet tested.

The classical Eötvös experiment tests the weak equivalence principle by comparing the ratio of passive gravitational mass to inertial mass for various substances. New tests of the Strong Equivalence Principle might include the comparison of precision clocks deriving their timing from different physical phenomena. Electric forces (atomic clocks), weak interactions (particle decay), and gravitation forces (orbits) would provide the most stringent tests.

Eötvös EXPERIMENTS

Earth-orbiting laboratories offer some advantages and some disadvantages for Eötvös-type experiments. The large, nearby active mass of the earth acting as driving force and the escape from suspension noise are primary gains; the large gravitational gradient along the direction of the force introduces a serious problem for unsymmetrical masses. Several approaches to solving the "tidal" problem are possible in principle, but these all probably require some on-station adjustments. An astronaut to interact with the apparatus in the early stages of the experiment could prove most helpful, but later on such interaction must be minimized.

The subpanel is aware of at least one ground-based Eötvös experiment in progress where an accuracy of 10^{-14} seems possible. (This estimate comes from scaling on-site tests with a working model.) Careful assessment of ground-based possibilities is clearly indicated for this experiment.

CLOCK EXPERIMENTS TO TEST THE STRONG PRINCIPLE OF EQUIVALENCE

The intercomparison of a hydrogen maser or a cesium beam clock with a molecular clock such as an ammonia maser or diatomic molecular beam clock would test the variation of the nuclear coupling constant relative to the fine structure constant as a function of gravitational potential. An intercomparison of a gravitational clock with a hydrogen maser would offer a test of the scalar contribution to the gravitational field which violates the strong principle of equivalence. The periodicity of a gravitational oscillator depends on "G" which in turn is a variable in the scalar-tensor theory.

The Shuttle may be useful in the development of a gravitational oscillator by providing a low "g" environment. Several designs of a gravitational clock have been studied, all of which require delicate and isotropic suspensions.

MEASUREMENTS OF "G"

One prediction of scalar-tensor theory is that, if one adopts units where elementary particle masses are constant in time, then the gravitational coupling constant is decreasing at a rate of about one part in 10^{11} per year. This is an effect of the general expansion of the universe and the scalar coupling between particles. The search for this effect is an important task of experimental gravitation; so far, no test direct or indirect has been decisive. Interpretation of geophysical data, effects on stellar evolution, and detailed studies of the earth-moon system have fallen short of the 10^{-11} per year goal, although there is hope that laser ranging to the moon may someday be understood with enough accuracy to look for secular change in the earth-moon distance.

Laboratory-type experiments to search for changing "G" have not approached the required accuracy. Essentially, one is trying to compare a gravitational force to an electrical force with high precision over a long period of time. Understanding the inevitable small changes in electrical forces has been the main problem. At this time, we do not see how an orbiting laboratory would improve these experiments by the required amount.

The measurement of the magnitude of "G" in terms of standard units is of some interest, although nothing of fundamental importance can be learned. If, however, a simple, inexpensive experiment could be designed to substantially improve on the current accuracy on "G" of $\pm 2 \times 10^{-3}$, it would be worthwhile.

GRAVITATIONAL RADIATION

Search for gravitational radiation is being carried out in several laboratories around the world. Earth-based efforts using cryogenically cooled bars and interferometric antennas should be able to set limits on the gravitational radiation flux that are factors of 10^4 smaller than present experiments. However, it is dubious whether these antennas will be able to set meaningful upper limits to the gravitational radiation by pulsars.

Space offers some unique opportunities to set up antennas to measure gravitational radiation from astronomical sources. Gravitational radiation varies the proper distance between free objects in proportion to their separation; in effect, it creates a time-varying strain in space. The large baselines possible in space, extending to the optimal separation, which is of the order of the wavelength of the gravitational wave, would allow the construction of gravitational antennas with vastly more sensitivity and possibly less noise than those on earth.

GROUND-BASED RESEARCH AND ON-GOING EXPERIMENTS

Although space offers some unique opportunities, much can still be learned from ground-based measurements. Clearly, for optimum scientific benefit from the space effort, experiments should not be done in space if they can be more easily and inexpensively done from the earth's surface. This will frequently be a difficult choice involving a balance between effort and expense on the one hand and improved accuracy on the other.

Large earth-based telescopes will, of course, continue to produce valuable cosmological data in the visible and near infrared. One can look forward to important new results in the coming decade of this fast accelerating field. Space experiments must capitalize on the unique advantages of being outside the atmosphere.

Efforts will continue with ground-based radio interferometers and planetary radar to obtain improved measurements of the bending of electromagnetic waves in the gravitational field of the sun and the relativistic time delay, respectively.

The search for gravitational radiation is being carried out in several laboratories around the world.

RELATIVITY EXPERIMENTS FROM SPACE AND UTILIZATION OF SPACE SHUTTLE

Listed below are several experiments as examples of how a space laboratory might contribute to research in relativity. These experiments seem to us at this time to give the best combination of feasibility and importance to our basic understanding of relativity. Uncertainties in laboratory developments and incomplete feasibility studies necessarily make these views myopic.

In rough order of priority, based on a feasibility/importance criteria, we suggest that the following experiments be considered:

- Cosmology Experiments
- Drag-Free Satellite

- Geodetic Gyro Precession
- Blackbody Radiation - Spectrum
  - Isotropy
- Eötvös Experiments
- Second-Order Gravitational Redshift
- Lense-Thirring Gyro Precession
- Strong Equivalence Principle Tests (Clocks)
- Solar Oblateness
- Solar Light Deflection
- Gravitational Radiation Experiments
- Measurements of "G"

If one considers only the scientific significance of these experiments, the order of priority changes as indicated below:

- Cosmological Experiments (including 2.7°K Blackbody Radiation)
- Drag-Free Satellite
- Gravitational Radiation
- Lense-Thirring Effect
- Geodetic Precession
- Strong Principle of Equivalence (Clocks)
- Second-Order Gravitational Redshift
- Eötvös Experiments
- Solar Light Deflection
- Solar Oblateness (optical measurements)

Some of the listed experiments require a force-free (i.e., zero-g environment). Residual accelerations inside the Shuttle vehicle are still too high to perform these relativity measurements. However, the Shuttle Sortie Laboratory provides excellent opportunities to test experiment hardware and concepts in a near zero-g environment which is otherwise not available. An engineering test flight could be a requirement with some of the experiments where the actual zero-g performance of instruments cannot be predicted from testing on the ground. Contamination of the environment around the Shuttle by spacecraft effluents will hinder the detection and measurement of very low levels of radiation from space.

The following experiments could be performed onboard the Shuttle vehicle:

- Some measurement of the general background radiation
- An Eötvös experiment
- Solar oblateness measurement
- The optical light deflection experiment

In all other cases the experiments require a free-flying module or automated spacecraft and the Shuttle could provide transportation into orbit.

SUPPORTING RESEARCH AND TECHNOLOGY

To measure extremely small relativistic effects requires advancements in instrumentation and technology in certain areas. Without performing a detailed analysis the following topics can be identified for research and technology development.

Drag-free satellite control is needed for several experiments. A drag-free control system with an acceleration limit of 10^{-10} g has been tested successfully on an experimental flight. However, an improvement by three orders of magnitude (10^{-13} g) is required for some experiments which indicates further development effort.

The technology to keep instruments and sensors at the temperature of liquid helium for extended periods of time in space has to be developed.

The cyrogenic environment is necessary for low-noise detection systems, superconducting devices, and to obtain extreme mechanical stability. The application of liquid helium space flight dewars is not limited to relativity experiments.

A laser tracking system providing accurate ranging and orbit determination of deep-space probes and to perform relativistic time delay measurements through the solar corona requires developments going beyond presently available laser systems. Improved infrared detectors and the technique of force-free suspension of proof masses are areas for advanced research and development.

APPENDIX B

RADIO ASTRONOMY IN SPACE FOR THE 1980's

LONG-WAVE RADIO ASTRONOMY SUBPANEL
ASTRONOMY WORKING GROUP
SPACE SHUTTLE PROGRAM

APPENDIX B

RADIO ASTRONOMY IN SPACE FOR THE 1980's

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This report outlines a program for radio astronomy in space for the next decade (1980's). The report of the Radio Astronomy Panel of the Astronomy Missions Board (AMB) contains a comprehensive evaluation of the scientific goals and observational requirements for a low frequency radio astronomy program in space. This document is intended only to update the AMB Report by briefly considering progress to date in low frequency space observations and the need for future missions, and by including space missions designed to expand the capabilities of VLBI observations. The introductory section is primarily from the AMB Report.

SUMMARY OF SCIENTIFIC PROBLEMS

The history of radio astronomy has amply demonstrated that it can be characterized as the "science of new phenomena". Cosmology, galactic structure, supernova phenomena, and relativistic astrophysics are a few of the many branches of astrophysics that have been revolutionized by radio discoveries. Radio investigations within the solar system have shown that the physical environments of the Sun, Mercury, Venus, and Jupiter are completely different from expectations, so different that the physical design of spacecraft is profoundly affected. The extent of the Van Allen belts of Jupiter and the magnitude of the Jovian magnetic field have far exceeded expectations. The structure of the solar wind has been studied from a few solar radii out to and beyond the Earth's orbit. Entirely unexpected phenomena such as the low-frequency noise bursts from Jupiter and the traveling solar noise bursts have been discovered and they display highly energetic processes that still are not understood.

Outside the solar system, entirely new classes of celestial objects have been discovered. The most dramatic are quasars and pulsars, neither of which were expected from optical observations. Whether quasars are cosmological or relatively local, they are uniquely energetic objects in which the effects of either strong gravitational and magnetic fields or the largest scale structure of the universe are displayed. Pulsars have been studied for so short a time that, although their promise is far greater, one can only be certain that a uniquely periodic, energetic process has been discovered that will, at the very least, allow us to map galactic magnetic fields and electron density irregularities. Radio galaxies, whose enormous radio output is so great that they can be detected at distances far greater than the limits of optical techniques, offer the promise of probing the universe to enormous red shifts. Supernova remnants such as the Crab Nebula and its associated pulsar are still not well understood, but once again it is clear that we are dealing with a highly energetic phenomenon which is not restricted to the epoch of the explosion, but continues today. Our own galaxy is pervaded by high-energy particles, the cosmic rays. Radio observations of the galactic radio background are directly related to the electron component of this relativistic gas. In fact, the close relationship between radio emission magnetic fields and high-energy processes is abundantly clear.

The contribution of radio astronomy to our understanding of the large-scale structure of the universe must rely upon our understanding of the physical conditions and processes in radio galaxies and quasars. We still cannot specify the absolute luminosity of a radio galaxy from radio measurements alone, although it is clear that thousands of the known radio galaxies are at or beyond the limits of optical spectroscopic observations. The radio galaxies most commonly show a power law spectrum, the flux continuing to increase through the lowest frequencies at which reliable ground observations can be made, approximately 8 to 10 MHz. At still lower frequencies, a cutoff imposed by plasma phenomena must limit the radio flux, but ground-based observations of low-frequency spectra are compromised by the highly variable absorption and scintillation effects of the ionosphere. Reliable observations from the ground could perhaps be made at 5 MHz, every 11 years near sunspot minimum, but reliable observations at lower frequencies must be made above the ionosphere.

CURRENT STATUS OF LOW FREQUENCY SPACE OBSERVATIONS

Utilizing electrically short dipole antennas, the integrated cosmic radio noise spectrum has now been determined accurately down to frequencies of the order of 100 kHz. Furthermore observations with several satellites and rockets all give consistent results. From simple models of the radio universe at these low frequencies, estimates of the cosmic ray electron spectrum at low energies

($0.1 \leqslant E \leqslant 1$ GeV), the properties of free-free absorption by the thermal plasma, and some information on the structure of the local galactic system has been obtained. The cosmic ray electron spectrum obtained by this method gives a greater flux of electrons at low energies than that obtained from direct measurements by satellites. This is expected if solar modulation modifies extensively the flux observed in the inner solar system. If solar modulation is not effective, then the flux in the near solar system differs from the average flux for the local spiral system. The free-free absorption accounting for the intensity decrease below a few MHz is consistent with current models of the interstellar medium with clouds of density $< \sim.04$ electrons/cc$>$ at a temperature of the order of $100°$K and intercloud space of density $<.03$ electrons/cc$>$ at a temperature of $10^3 \leqslant T \leqslant 10^4$ °K. However, the observations at the lowest end of the spectrum suggest that the Razin effect becomes significant and adds to the absorption process.

Additional dipole observations well removed from the very noisy terrestrial environment and at low frequencies would be valuable, but the major thrust must be to obtain spatial resolution.

The first attempt to provide better angular resolution than that of a dipole was made with the RAE-1 satellite using a 229 meter "V" antenna. Since launch in July 1968, this satellite has observed the cosmic noise background with receivers covering frequencies in the 1 to 10 MHz range. Approximately four years of data have now been processed in the preparation of maps at selected frequencies. RAE-1 is in a 6000 km circular orbit where the various forms of intense terrestrial noise, in addition to solar bursts, seriously limit the times of observations of the cosmic background. However, maps are now being analyzed and interpreted. For example, the low background in the Gum Nebula region has been investigated and interpreted to give a value of electron temperature in the Gum Nebula of $T_e \approx 5.7 \times 10^4$ °K. Although no discrete extra-galactic sources have been seen by RAE-1, owing to a lack of angular resolution, the isotropic integrated background due to all the radio sources in the universe has been detected and shown to have a spectral index $\simeq 0.8$.

SOLAR ACTIVITY

The investigation of traveling solar radio bursts over the frequency range from 10 MHz to 30 kHz has led to a better understanding of the properties of the interplanetary medium and the propagation of energetic particles and shock waves from 10 solar radii out to 1 AU from the sun. During the years of maximum solar activity hundreds of thousands of type III, fast drift, bursts were observed each year in the hectometric range. These bursts occurred individually, in complex groups, and in storms lasting for a half rotation of an associated active region across the sun. Within the past few months, positive identification has been made of type II busrts out to 1 AU. Several "U" bursts out in the interplanetary medium have been observed and analyzed, and recently it appears that a type IV burst has been observed beyond 10 $R_\odot$.

Through the investigation of long-term storms of type III events and the geometric effect on time of propagation for the radio emission, it was possible to determine a distance scale for the radio emission as well as the average exciter speed between 10 and 40 $R_\odot$. In addition, an extremely effective method of direction finding with a spinning dipole has been developed for determining both the direction of arrival of the radio emission and some information on source size. In effect the data as modulated by the antenna rotation is cross correlated with the known antenna pattern, and the phase is adjusted for maximum correlation. This phase can be simply related to direction relative to a fixed reference direction such as the center of the sun. This technique has been used extensively to study magnetospheric and solar radio bursts and to some degree for investigating the distribution of cosmic noise.

This technique has led to the tracking of type III exciter particles from the sun to 1 AU. For example, the spiral path of the exciter particles can be observed and thus the gross interplanetary magnetic field configuration can be indirectly observed. Evidence is increasing that type III radio emission at long wavelengths is observed to occur mostly at the second harmonic of the plasma frequency. With this in mind, the density versus distance scale derived from the radio method over 1 AU, is consistent with solar wind measurements at 1 AU and K coronagraph observations at 10 $R_\odot$. Comparison of radio observations and energetic electron measurements at 1 AU confirm that the exciter particles are electrons with an energy distribution between 10 - 100 KeV. The radio observations are leading to a clearer understanding of the properties and propagation of these electrons, of the nature of the interplanetary density and field configuration, and of the evolution of the flare process. In addition the more recent observations of type II events will contribute much to the understanding of shock wave propagation.

MAGNETOSPHERIC RADIO NOISE

A rather interesting array of radio processes are observed to occur within the terrestrial environment. These include radio emission from particle precipitation into the auroral region, noise of local plasma origin, and thunderstorm activity. The investigation of these phenomena are of importance not only for magnetospheric and atmospheric physics, but also as they relate to the more general questions of radio astrophysics. Furthermore these investigations will be of great importance in the planned radio experiment on the Mariner-Jupiter-Saturn mission.

CURRENTLY PLANNED MISSIONS

RAE-B

The second RAE will be placed into an 1100 km circular orbit about the moon in mid 1973. This mission provides a number of important advantages over the RAE-1 mission, including the opportunity to observe down to the plasma frequencies of the interplanetary medium, ~10 kHz. Of equally important advantage is the large reduction of contamination caused by radio noise of terrestrial origin. In addition to the path loss for such noise, the moon will at times shield this contribution (there is onboard data storage). Therefore it will be possible to produce better quality maps of the cosmic background and to look for sources such as Jupiter and the Crab Nebula, which could not be detected in the presence of the intense terrestrial noise levels.

HELIOS

The Helios solar probe payload, which will travel to 1/4 AU of the sun, also contains a dipole radio experiment, primarily for the investigation of solar radio bursts and the interplanetary medium in frequency range 25 kHz - 13 MHz. This is a joint USA/German Mission.

IME (INTERNATIONAL MAGNETOSPHERIC EXPLORER)

This heliocentric mission payload contains an experiment for the 3 dimensional mapping of the positions of solar radio bursts. This unique experiment utilizes the spinning dipole concept in two dimensions, so that the direction of the radio burst can be located in space out of the spin plane. Tracking of traveling solar radio bursts should provide the first opportunity to investigate the solar wind and magnetic field configuration out of the ecliptic plane.

MJS (MARINER-JUPITER-SATURN)

The Mariner-Jupiter-Saturn mission to the outer planets will contain a radio experiment, again utilizing short dipole antennas. This experiment capable of spectral, polarization, and limited directional observations will provide the close investigation of the radio environment of Jupiter, as well as Saturn in the low frequency range. These investigations will certainly contribute to our understanding of the composition and dynamics of these planetary magnetospheres and for example of the unique way in which Io interacts in this process. During the cruise mode of this experiment, equally valuable data will be obtained about the outer interplanetary medium and cosmic noise background.

FUTURE REQUIREMENTS

A system providing higher angular resolution, of the order of a few square degrees, remains the most pressing need at low frequencies. Such a system is essential for investigation of cosmological sources and for a detailed investigation of the continuum background, as well as some solar system sources. Aside from the potential for the discovery of new phenomena resulting from wave-particle interactions predicted to occur at long wavelengths, the investigation of discrete sources at long wavelengths can shed considerable light on the composition, dynamics, and evolution of such objects.

Two approaches have been considered for the attainment of the required angular resolution from spacecraft systems. These are the filled aperture array, such as the KWOT (Kilometer Wave Orbiting Telescope), and an aperture synthesis system utilizing two spacecraft, e.g. the RAE-C and D study. Both systems which provide the needed resolution, have been studied in detail and appear to be feasible, although the interferometer scheme appears to be less expensive and capable of yielding a useful increase in angular resolution for studies of transient solar and planetary radio bursts.

In addition to this major goal for radio astronomy, the scientific value of a Jupiter orbiter incorporating a complete radio physics payload is quite clear. The MJS will provide important exploratory observations which will be necessary in establishing the parameters of an orbiting radio physics experiment.

VLBI (VERY LONG BASE-LINE INTERFEROMETRY

This section considers the current status of certain VLBI observations and some potential advantages which can be derived from space missions. What is proposed here is that the need for such experiments, and their technological feasibility should be investigated.

PRESENT STATE OF OBSERVATION

The developments of ground-based very-long-baseline interferometry (VLBI) have shown that both quasars and interstellar H_2O masers exhibit structure that cannot be resolved with existing ground-based telescopes (baselines $\lesssim$ 10,000 km). Higher frequency observations of quasars, to get baselines that are longer in number of wavelengths, do not yield resolution of the sources because the higher in frequency one observes the more compact the sources become, since the volume over which the components are optically thick diminishes with increasing wavelengths. Space baselines are therefore necessary.

H_2O Masers

The H_2O maser observations are valuable for two reasons. First, the US-USSR observations show that the masers associated with W49 have structures less than 0.0003 arc sec in size. This demonstrates that interstellar scattering at 1.3 cm wavelength is not a controlling factor, and one can reasonably expect achievement of 10^{-5} arc sec resolution at high galactic latitudes, if some of the sources exhibit such fine structure. Secondly, the sources are strong, and thus would provide a sure calibration of any operating space VLBI system. The intrinsic scientific interest in studying the H_2O masers lies in the apparent association of the maser sources with regions of active star formation.

Quasars

The scientific puzzles associated with quasars remain unresolved, despite many years of intensive study. Intrinsically, the understanding of the highly energetic processes that drive them is frustrated by the lack of data. The extra information afforded by VLBI studies has yielded a new puzzle in recent years. Motions are observed that can perhaps be interpreted as evidence for motions greater than the velocity of light. There are alternative explanations, the most likely being that complex motions of many sub-components are interpreted, in the simple models, incorrectly. Only by mapping the sources completely, with a more complete range of baseline coverage than has been heretofore attempted on the ground, can the controversy be settled.

Cosmology

Another class of potential observations makes use of the fact that the very large red-shift of many quasars implies extraordinarily great distances. The structures of the very distant quasars, compared to the relatively nearby examples such as 3C273, thus give an observational means of approaching the question of quasar evolution and the large-scale geometry of space. If quasars exhibit sufficiently small-scale structure, one can project, in fact, a new age of positional astronomy. A resolution of 10^{-5} arc sec is a dimension of the order of one light-year at the Hubble distance, assuming Euclidean geometry and if astrometric techniques of space-VLBI can be developed, an entirely new range of problems, related to the geometry of the universe on the very largest scale, can be attacked.

The program can be attacked in stages, the first of which would be designed to give data on the problems that are known to exist, and lay the groundwork for the study of the more speculative programs that might follow.

FIRST MISSION

Two kinds of VLBI space platforms can be used. First, a vehicle in an eccentric orbit, reaching from 300 km to 30,000 km or more, would overlap earth baselines for which the results are known.

It would be natural to use 1.3 cm as one of the basic wavelengths, both to study maser sources and to calibrate the system. Other frequency receiving capability would probably be included also. The dish, when unfolded, should be at least 10 to 20 m in size, and be capable of one arc minute pointing.

The second kind of VLBI space platforms would utilize a close-in orbit, and would, when used with existing ground stations, give virtually complete coverage of the Fourier transform plane. The instrument might well be carried by the Shuttle in the Sortie mode, or dropped off as a free-flier. The reflector, when unfolded, should be of the order of 10-20 m diameter, and the experiment could probably share operations with other missions, if they involve keeping the Shuttle in a fixed orientation for reasonable periods of time. For example, sharing with solar observations would be a natural possibility.

INTERNATIONAL COOPERATION

It is clear that one attractive feature of both classes of experiment is their natural adaptation to international cooperation. All ground-based radio telescopes that are adequately instrumented for ground-based VLBI (this will be the case for all the principal radio telescopes in the world) can participate, and enhance, the observations.

FAR-OUT COSMOLOGY

The mission to support the more speculative cosmological astrographic observations would depend on the outcome of the eccentric-orbit mission. All we can say at this time is that the largest possible baselines on earth have failed to give complete resolution of all sources, and one would find out from the 30,000 km orbit whether suitable sources exist for investigation at still longer baselines. In order to eliminate the effects of the earth's atmosphere and ionosphere, it would be desirable to have a pair of VLBI platforms for the astrographic work, but the specific system specifications would depend upon the experience gained with single-platform earth-to-space or earth-to-moon VLBI observations. Measurement of radio source positions with accuracy of 10^{-6} arc sec should be feasible if suitable sources exist, and would open entirely new vistas in the study of the universe.

ROLE OF THE SHUTTLE

Hectometer and kilometer radio observations conducted in space require instruments placed well above the terrestrial ionosphere. Therefore these observations cannot be accomplished from the Shuttle itself. However if "tug" missions are launched from the Shuttle into higher orbits there may be great advantage for any of the proposed missions utilizing VLBI and kilometer observations. Using the Shuttle as a launch base, for example, it would appear that two or more spacecraft could be launched into appropriate orbits in a controlled manner. Another potential use of the Shuttle would be the flight testing of large telescope systems such as the KWOT. In addition, the Shuttle shows great promise in the millimeter and IR spectral regime, where molecules in the earth's atmosphere absorb radiation. Here we would envision the use of existing microwave radiometric techniques on a small, precision dish — a 3 meter dish at 1 mm ($\sim$300 GHz) would yield an angular resolution of $\sim$1 minute of arc. Such an instrument should be equipped with a broad-band radiometer "back-end" for studies of continuum sources such as quasars, HII Regions, and planets, and with a spectral line "back-end" for studies of radiation from molecular clouds in our galaxy. A program to capitalize on this opportunity needs further study.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1972—735-969/737

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